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RESEARCH MEMORANDUM

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By Lindsay J. Lina, Garland J. Morris,
and Robert A. Champine

Langley Aeronautical Laboratory
Langley Field, Va.

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SUMMARY

Flight tests and analog-computer studies using flight-test results have been made of a swept-wing jet fighter in the landing condition to determine the factors which influence a pilot in selecting the minimum approach speed for carrier-type landings.

Many of the factors which influenced the pilot in the determination of the approach speed of this airplane occurred in approximately the same speed range, and the quantitative determination of the influence of each factor was not possible in these tests. Loss of lateral-control effectiveness with increasing angle of attack limited the approach speed in rough air but was of secondary importance in smooth air. Poor altitude and speed control at speeds below that for minimum drag was a major factor as was the loss of longitudinal static stability at high angles of attack. Engine thrust response was sluggish at low speeds and contributed to poor wave-off performance. Visibility over the nose of the airplane was inadequate at low speeds, and touchdown-attitude restrictions by the landing-gear configuration were considered objectionable.

INTRODUCTION

The requirements for strength and capacity of arresting-gear equipment have been greatly increased with the modern jet-driven carrier-based airplanes as compared with earlier aircraft generations. This increase in demands on arresting equipment has arisen largely from the greater mass and higher stalling speeds of the newer airplanes. However, another important factor is the tendency for these newer airplanes

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to require a relatively large speed margin above the stall for safe operation in carrier-type landing approaches. This tendency toward larger approach-speed margins is of considerable concern to the Navy. Because of the uncertainty of the causes, the higher approach speeds cannot be rationally accounted for in predicting arresting-equipment requirements for future airplanes.

The high approach-speed margins have been attributed by pilots to a variety of factors, including difficulty of controlling altitude and speed at lower speeds, touchdown-attitude limitations, visibility deterioration at high attitudes, and wave-off response.

An investigation in the form of an analog study of some effects of airplane configuration on the response to longitudinal control was made and is reported in reference 1. An investigation of landing-approach characteristics reported in reference 2 showed the effects of boundary-layer control in flight tests of a swept-wing fighter. Flight and simulator studies of some effects of airplane and engine configurations on the minimum approach speed for carrier-type landings were made in reference 3.

In the investigation described in this paper, an attempt has been made to evaluate quantitatively some of the factors involved in the pilots' choice of approach speeds for carrier-type landings and to study the problems encountered at speeds lower than the recommended approach speed. Flight tests were made with a Grumman F9F-7 airplane, a jet fighter intended for carrier operation. The airplane was flown by one pilot for all flight tests. Flight measurements of longitudinal aerodynamic characteristics including longitudinal stability derivatives and some measurements of lateral-control characteristics were made at altitudes of several thousand feet. Measurements of longitudinal airplane motions and control deflections were recorded near the ground during field-carrier landings. The landings were made at and below the minimum recommended carrier approach speed (ref. 4). The time histories of field-carrier landings presented in this report were made with an Allison J33-A-16A engine installed in the airplane. Measurements in several landing approaches were also recorded for a Pratt & Whitney J48-P-8 engine installation but are not presented as time histories because no significant differences were noted in the time histories. Data obtained in landing approaches with each of the two engines are included in a brief statistical study of the elevator and throttle movements used by the pilot during the approaches. Transient thrust characteristics of both engines were measured on the ground.

Computations of the airplane motions and elevator movements in a "high dip" (a command from the landing-signal officer for an altitude loss) maneuver at different airspeeds were made by an analog-computer simulation of the F9F-7 airplane equipped with an autopilot sensitive to changes in altitude, attitude angle, pitching velocity, and flight-path angle. The analog study was made with the assumption of a constant throttle setting and was intended to determine the airplane response to elevator movements necessary for altitude control.

SYMBOLS

a_Z normal acceleration, g units

$\bar{c}$ mean aerodynamic chord

C_D drag coefficient

C_{D_g} gross drag coefficient uncorrected for effects of control deflection and pitching velocity

C_L lift coefficient

C_{L_g} gross lift coefficient uncorrected for effects of control deflection and pitching velocity

$$C_{L_q} = \frac{\partial C_L}{\partial \frac{\dot{\theta}\bar{c}}{2V}}$$

$$C_{L_{\dot{\alpha}}} = \frac{\partial C_L}{\partial \frac{\dot{\alpha}\bar{c}}{2V}}$$

$C_{L_{\delta_e}}$ rate of change of lift coefficient with elevator deflection per degree

C_m pitching-moment coefficient about $\frac{\bar{c}}{4}$

$$C_{m_q} = \frac{\partial C_m}{\partial \frac{\dot{\theta}\bar{c}}{2V}}$$

$$C_{m_{\dot{\alpha}}} = \frac{\partial C_m}{\partial \frac{\dot{\alpha}\bar{c}}{2V}}$$

$C_{m_{\delta_e}}$ rate of change of pitching-moment coefficient with elevator deflection per degree

D	differential operator with respect to time, d/dt
F_g	gross thrust, lb
F_n	net thrust, lb
f_1, f_2, f_3	functions
g	acceleration due to gravity, ft/sec^2
h	altitude, ft
h'	altitude prescribed for standard maneuver used for input of analog computer, ft
Δh	altitude change, ft
I	moment of inertia in pitch, slug-ft^2
p	static pressure, lb/sq ft
p_t	tail-pipe total pressure, lb/sq ft
q	dynamic pressure, lb/sq ft
S	wing area, sq ft
t	time, sec
V	velocity, ft/sec unless otherwise noted
V_c	calibrated airspeed, knots
V_{c_e}	equivalent calibrated airspeed, $V_c\sqrt{\frac{14,830}{W}}$, knots
V_o	initial airspeed prescribed for standard maneuver for input of analog computer, ft/sec
$\dot{V}$	time rate of change of velocity, ft/sec^2
W	airplane weight, lb
w_a	weight of inlet air, lb/sec
x	distance of center of gravity from $\bar{c}/4$

α	angle of attack of fuselage reference line, deg
$\dot{\alpha}$	rate of change of angle of attack, radians/sec
γ	flight-path angle, positive in climb, deg
$\dot{\gamma}$	rate of change of flight-path angle, radians/sec
δ_e	elevator deflection, deg
δ_{e_o}	initial elevator deflection, deg
δ_f	flaperon deflection, deg
δ_t	throttle deflection, deg
θ	attitude angle in pitch, positive with nose-up inclination of airplane, deg
$\Delta\theta$	attitude-angle change, deg
$\dot{\theta}$	pitching velocity, radians/sec
$\ddot{\theta}$	pitching acceleration, radians/sec^2
θ'	attitude angle prescribed for standard maneuver for input of analog computer, deg
ρ	mass density
$\ddot{\varphi}$	rolling acceleration, radians/sec^2

AIRPLANE AND TEST EQUIPMENT

Airplane

A swept-wing Grumman F9F-7 jet-fighter airplane was used for the flight investigation herein. The flaps were fully deflected and the slats and landing gear were fully extended for all tests. A three-view drawing of the airplane with a sketch of the wing with slat extended and flap deflected is shown in figure 1. Photographs of the airplane are shown in figure 2 and pertinent dimensions of the airplane are listed in table I.

Longitudinal control of the airplane is maintained by means of manually operated elevators. An increment of maneuvering-force gradient is provided by a bobweight (statically balanced by an equalizer spring at 1 g) attached to the forward control sector. A stability spring, or system bungee, is automatically coupled into the system with flaps down to improve static stability and provide satisfactory trim change at low speeds. A pull static force of about 15 pounds is required to hold the stick in neutral on the ground at zero speed with flaps down. The airplane is trimmed by means of an electrically adjustable stabilizer.

Spoiler-ailerons, which are called flaperons, are used for lateral control of the airplane. These spoilers, or flaperons, are attached at their leading edge by means of a piano-type hinge to the upper surface of the wing at about the 70-percent-chord line and extend from 46 percent to 96 percent of the wing semispan. The flaperon chord perpendicular to the hinge line is about 12 inches. The flaperons are actuated hydraulically, and lateral-control feel is provided by a centering spring and cam attached to the stick. The feel for full stick travel is about 16 pounds. The variation of stick force with flaperon deflection is nonlinear and exhibits considerable hysteresis. Lateral trim is provided by a small trimmer aileron on the left wing tip.

Directional control was obtained by means of rudder pedals mechanically linked to the rudder. The airplane was equipped with an electronic yaw damper which was in operation on "high" gain during the tests. The ranges of control motions are given in table II.

Instruments

All measurements were recorded photographically by standard NACA recording instruments which were synchronized by a 0.1-second timer. The range and the reading accuracy of the instruments are listed in table III. The overall accuracy is believed to be within about twice the reading accuracy of the instruments. Corrections for lag of the recording instruments were applied in the data analysis.

Control motions of the throttle, elevator, stabilizer, and flaperons were obtained from control position recorders. Angular velocities and angular accelerations in pitch and roll were recorded by angular-velocity and acceleration recorders. Mechanical accelerometers recorded normal and longitudinal accelerations. Attitude-angle measurements were made with a sun camera as described in reference 5. The uncorrected angle of attack was obtained from a vane mounted on a nose boom about 68 inches ahead of the airplane. Free-stream temperature was obtained from a resistance bulb mounted under the fuselage.

Measurements of impact pressure and static pressure were obtained by using a pitot-static head mounted on the nose boom. The static-pressure source was about 83 inches (or about 1.1 times the maximum fuselage diameter) ahead of the nose of the airplane. A statoscope was used to measure differential static pressure in order to determine small altitude changes from a reference altitude of the pilot's choice.

Measurement of tail-pipe total pressure was from a single small pitot tube mounted about 14 inches behind the turbine blades and 2.5 inches from the wall of the tail pipe. Measurement of inlet total pressure was from a pitot tube mounted normal to and about an inch from the forward engine-inlet screen. The tail-pipe pressure was measured by using the static-pressure source for a reference pressure and the inlet pressure was referenced to the total pressure from the nose boom. A static-thrust stand was used to measure thrust on the ground with a maximum error of about ±50 pounds.

PROCEDURES

Calibration of Airspeed Head and Angle-of-Attack Vane

The airspeed installation was calibrated by pacing the F9F-7 airplane with an airplane having an airspeed installation with an established calibration.

The angle-of-attack vane was calibrated by measuring the attitude angle with the sun camera and by determining the average flight-path angle in several level-flight runs which were at constant speed and covered the angle-of-attack range necessary for these tests. The measured flow angle of the vane was corrected for boom misalignment, boom bending, and the effects of pitching velocity.

Thrust Measurements

Gross thrust and tail-pipe pressure were calibrated on a static-thrust stand by operation at various desired stabilized engine speeds. Measurement of total pressure at a single point in the tail pipe was used as an index of gross thrust. The variation of the ratio of gross thrust to static pressure F_g/p with the ratio of tail-pipe total pressure to static pressure p_t/p obtained in the calibration was used to determine gross thrust in flight. Net thrust in flight was obtained as the gross thrust minus the initial momentum rate of the inlet air as shown in the following equation:

$$F_n = F_g - \frac{w_a V}{g}$$

Estimation of the mass rate of airflow was made from charts in the engine manufacturer's handbook by using engine speed, free-stream temperature, and the total pressure measured at the forward engine screen. Errors in net thrust resulting from the use of only one pickup location for measurement of the engine inlet total pressure are believed to be small for these low-speed tests.

Transient thrust characteristics of the engine were obtained on the ground by abrupt movements of the throttle while continuous records were made by using the airplane instrumentation.

Longitudinal Stability and Control

Measurements were first made to obtain gross values of aerodynamic lift coefficient, aerodynamic drag coefficient, and angle of attack without correction for effects of stabilizer deflection, elevator deflection, or pitching velocity. The lift and drag coefficients were obtained from measurements taken in level trimmed flight, push-pull maneuvers, and a stall.

Stability derivatives were calculated from data obtained in level flight and push-pull maneuvers at center-of-gravity locations varying from 27 percent to 30 percent mean aerodynamic chord. The values of C_L, $C_{L_{\delta_e}}$, $\left(C_{L_q} + C_{L_{\dot{\alpha}}}\right)$, C_m, $C_{m_{\delta_e}}$, and $\left(C_{m_q} + C_{m_{\dot{\alpha}}}\right)$ at several fixed angles of attack were evaluated by a least-squares method using the equations of motion in matrix form in a manner similar to that in reference 6. The determinations of pitching-moment coefficients were made by using measurements of pitching acceleration. Inasmuch as pitching accelerations were measured directly and the stability derivatives varied with angle of attack, the equations of motion were not changed to the integral form as in reference 6.

The effects of pitching velocity, rate of change of angle of attack, and elevator deflection on the drag coefficient were approximated as a combined effect resulting from lift changes produced by the combination. The gross drag coefficient was found to vary in the following manner:

$$C_{D_g} = C_D + f_1(\alpha)f_2\left(C_{L_g} - C_L\right)$$

where

$$f_2\left(C_{L_g} - C_L\right) = f_3(\dot{\alpha},\dot{\theta},\delta_e)$$

The equation representing the best fit to the flight data was found to be

$$C_{D_g} = C_D + \left[0.00954(\alpha + 6.3^{\circ})\right]\left(C_{L_g} - C_L\right)$$

Lateral Control

Flaperon control data were obtained from maneuvers in which flaperon-control movements were initiated from straight and level flight and the airplane was allowed to roll beyond the angle of bank necessary to obtain the peak in rolling velocity. A chain fastened to the stick provided a stop for sidewise motion and thus permitted nearly step-input stick motions.

Field-Carrier Landings

Field-carrier landings at the Naval Test Center, Patuxent, Maryland, were made in order to investigate handling qualities of the airplane at normal carrier approach speeds and also at slower speeds which were considered unsatisfactory for carrier-type approaches. All approaches and landings were directed by a qualified landing-signal officer who was stationed on the runway about 4,000 feet from the approach end. The standard operational practices were modified slightly to allow for a longer straight-in final approach in order for the airplane to land on the runway in the event that an inadvertent excessive rate of descent resulted in a landing short of the intended area. This was a real possibility at the very slow approach speeds. The pilot's opinion was that this variation from the standard pattern had little or no effect on his evaluation of the approach problem.

The landings were made only in daylight with wind velocities of about 4 or 5 knots with very little turbulence.

The airplane approached the end of the runway about 25 feet above the ground with an airspeed somewhat above the speed intended for investigation. The pilot maintained nearly constant altitude and gradually reduced his speed to the intended steady value for the final portion of the approach up to the "cut" point. This portion of the approach generally occurred in the last 10 seconds before the cut. Data were recorded in the final approach over the runway and records were also obtained in a wave-off resulting from a missed approach.

Analog Simulation of Airplane and Pilot

In an effort to determine what the response of the pilot and airplane would be to the attempted performance of a simple maneuver (high dip) at various airspeeds, the longitudinal motions of the airplane under the control of an autopilot were calculated with an analog computer. The longitudinal aerodynamic coefficients and stability derivatives which were evaluated from flight data as nonlinear functions of angle of attack were used in the following equations of motion of the airplane:

$$\dot{V} = \frac{F_n g}{W}\cos\left(\alpha - 1.3^\circ\right) - \frac{\rho V^2 S g}{2W}\left\{C_D + \left[0.00954(\alpha + 6.3^\circ)\right]\left[C_{L_{\delta_e}}\delta_e + \left(C_{L_q} + C_{L_{\dot{\alpha}}}\right)\frac{\dot{\theta}\bar{c}}{2V}\right]\right\} - g\sin\gamma$$

$$\dot{\gamma} = \frac{\rho S g}{2W}\left\{V\left[C_L + C_{L_{\delta_e}}\delta_e + \left(C_{L_q} + C_{L_{\dot{\alpha}}}\right)\frac{\dot{\theta}\bar{c}}{2V}\right]\right\} + \frac{F_n g}{WV}\sin\left(\alpha - 1.3^\circ\right) - \frac{g\cos\gamma}{V}$$

$$\ddot{\theta} = \frac{\bar{c}}{I}\left(\frac{x}{c} - 0.25\right)\left(1 + \frac{\dot{\gamma}V}{g}\right)W + \frac{S\bar{c}}{I}\frac{\rho V^2}{2}\left[C_m + C_{m_{\delta_e}}\delta_e + \left(C_{m_q} + C_{m_{\dot{\alpha}}}\right)\frac{\dot{\theta}\bar{c}}{2V}\right]$$

The input to the analog computer included fixed values of air density, thrust, weight, and center-of-gravity location as well as initial values of airspeed, angle of attack, and flight-path angle. The automatic pilot controlled the longitudinal motion of the airplane by deflecting the elevator as a function of pitching velocity, flight-path angle, and the difference between the altitude and attitude angle of the airplane from the programed time histories of altitude and atitude angle for the high dip. The equation for the output of the autopilot was

$$\delta_e - \delta_{e_o} = \frac{+K_1(h - h') + K_2(\theta - \theta') + K_3\gamma + K_4\dot{\theta}}{1 + 0.2D}$$

where K_1, K_2, K_3, and K_4 were gain settings of the autopilot. The gain settings and time lag of the autopilot were intended to simulate crudely a human pilot. A simplified illustration of the airplane and autopilot system is shown in the block diagram of figure 3.

The programed time histories of altitude and attitude angle in the maneuver are shown in figure 4. Gain settings for the autopilot were selected in such a way as to perform the maneuver at 145 knots reasonably well with a damped motion. The adjustments were made at an initial velocity of 145 knots because the airplane responded reasonably well in flight at that speed.

A comparison of the computed motions of the airplane (without autopilot) with an actual flight maneuver was made by approximating the elevator deflection recorded in a flight maneuver with a step function for the input to the analog computer.

RESULTS AND DISCUSSION

Measurement of Airplane and Engine Characteristics

Engine thrust response.- Response to abrupt throttle movements of the Allison J33-A-16A and Pratt & Whitney J48-P-8 engines installed in the F9F-7 airplane is shown in figure 5. Throttle motions faster than some fixed rate (not determined by these tests) have no effect on the rapidity of thrust increase or decay. Beyond this limiting rate of throttle movement, engine acceleration and deceleration are governed only by the engine control unit and inertia.

For the approaches recorded in these tests, the pilot's throttle movements were nearly step inputs and therefore were more rapid than the engine response. In the opinion of the pilot the thrust response of the J33-A-16A engine was slow. The slow response of this engine caused him concern because the thrust response was not fast enough to correct or hold constant the desired speed and altitude. This effect became more noticeable as the speed was decreased below 120 knots and was completely unsatisfactory at the lowest speeds of about 105 knots (approximately 2,500 pounds of fuel remaining).

The thrust response of the J48-P-8 engine was different in that the rate of thrust increase was twice that of the J33-A-16A engine. The maximum static thrust of both engines installed in the airplane was about the same for standard sea-level conditions. The pilot felt that the increased rate of change of thrust provided by the J48-P-8 engine was a significant improvement; however, at speeds below the recommended approach speed (about 120 knots) the engine thrust response was still not fast enough to correct deviations in speed and altitude as quickly as desired.

Trim lift coefficient and drag coefficient.- The variations of gross lift coefficient with drag coefficient and angle of attack are shown in figure 6. The values contain the effects of stabilizer and elevator deflection and pitching velocity but, except for induced-flow effects, do not include thrust forces on the airplane. The scatter of data in the maneuver is not large since the pitching velocity in the maneuver was small. The break in the lift curve and the large drag increase at angles above 10° indicate the influence of separation on the sweptback wing. The large hysteresis loops in the variations of lift coefficient and drag coefficient with angle of attack in the stall apparently result from delay in reattachment of separated flow. The individual data points were obtained in succession at 1-second intervals in the stall recovery.

Speed for minimum drag.- The variation with airspeed of maximum available thrust and the variation with airspeed of drag computed for an approach with no thrust and for a power approach are shown in figure 7. These values have been computed for an airplane gross weight of 14,830 pounds which is typical for landing.

The speed for minimum drag (about 120 knots) corresponds closely with the speed at which the pilot began to recognize poor speed control. The pilot reported increasingly greater difficulty in maintaining constant speed and altitude as speeds were reduced below the speed for minimum drag. The speed for minimum drag has also been found to be a significant factor in the selection of approach speed for another swept-wing fighter airplane (ref. 2). An analysis of stability of an airplane for speeds below the speed for minimum drag is given in reference 7.

Figure 8 illustrates the divergence in speed which occurs when the pilot attempts to hold constant altitude after a drag disturbance at a speed below the speed for minimum drag. A drag brake was opened in flight (at time = 0) then closed to slow the airplane from its trim speed with the throttle setting remaining constant. The measured airspeed was converted to equivalent calibrated airspeed for an airplane gross weight of 14,830 pounds. At speeds below that for minimum drag, the decreased speed resulted in increased drag and a resulting thrust deficiency which caused a continued decrease in speed and increase in drag. At speeds above that for minimum drag the decreased speeds resulted in decreased drag and a thrust excess which returned the airplane to its original airspeed. The inadvertent altitude changes which occurred during the runs were small and the resulting exchange of potential and kinetic energy had little effect on the velocities.

Longitudinal aerodynamic characteristics.- A statistical analysis was made from data obtained in flight to determine the longitudinal aerodynamic characteristics. The variations with angle of attack of the effects of pitching velocity, rate of change of angle of attack, and elevator deflection on the lift, drag, and pitching moments were determined for a range of angle of attack between 0° and 17°. The angle-of-attack range was limited to include data for which sufficient measurements were available. The effects of different stabilizer settings were eliminated by correcting the elevator movements to deflections equivalent to a stabilizer setting of -2.8°. The ratio of stabilizer effectiveness to elevator effectiveness was found from flight measurements to be about 2.5.

Variations of the longitudinal aerodynamic characteristics with angle of attack are shown in figure 9. The plot of lift coefficient due only to angle of attack C_L shows that the lift-curve slope decreases at an angle of attack of about 11°. The rate of change of lift coefficient with elevator deflection $C_{L_{\delta_e}}$ remains nearly constant over the entire range of angle of attack. The value of the combined derivative $C_{L_q} + C_{L_{\dot{\alpha}}}$, however, increases in an irregular manner with increasing angle of attack. The cause of this behavior is unknown.

The variation with angle of attack of the pitching-moment coefficient about the 25 percent mean aerodynamic chord and the effects of elevator deflection, pitching velocity, and rate of change of angle of attack on the pitching-moment coefficient are shown in figure 9(b). A pitching-moment break usually associated with tip stall occurs at an angle of attack of 12°. Accuracy of the pitching-moment variation with angle of attack at angles of attack from 15° to 17° is reduced because fewer data were available. The elevator effectiveness increases as angle of attack is increased from 8° to 12° and remains constant between 12° and 17°. Damping in pitch remains nearly constant up to 8° angle of attack and increases with angle of attack up to 17°.

The variation with angle of attack of drag due only to angle of attack is shown in figure 9(c).

Stick-fixed neutral point.- The variation of neutral point with angle of attack is presented in figure 10. The neutral point was calculated by using the longitudinal aerodynamic characteristics and stability derivatives of figure 9. The neutral point remains at 33 percent mean aerodynamic chord as the angle of attack is increased to about 7°, after which it moves rearward as the angle increases to 11°, then, forward abruptly at angles greater than 11°. The airplane becomes neutrally stable at lower angles of attack as fuel is consumed because of the rearward movement of the center of gravity. The center-of-gravity location and weight of the airplane without fuel and with the fuel loading for each of six field-carrier approaches, which are discussed subsequently, are also shown in figure 10. The neutral-point shift probably results from changes in the stall area near the wing tip. The pilot believes the low, or negative, static margin causes him considerable difficulty in maintaining longitudinal control in the approach.

Lateral control.- Loss in effectiveness of the flaperons at high angles of attack is apparent in figure 11 which shows the variation with angle of attack of rolling acceleration divided by dynamic pressure for three flaperon-deflection angles. The data in figure 11 obtained at three fixed flaperon deflections were cross-plotted in figure 12 to indicate the loss of flaperon effectiveness with approach speeds decreasing below 136 knots. The cross plots were calculated for a gross weight of 14,830 pounds. Departure of the cross plots from linearity at low approach speeds is indicative of the growing region of low-energy flow on the upper surface of the wing as the boundary layer thickens and separation ultimately begins.

The resulting "dead spot" in the effectiveness of the control at small deflections causes a lag of the airplane response to lateral control movement at low approach speeds. This lag would be expected to be, and was, objectionable to the pilot. For average weather conditions the pilot believes the minimum approach speed of this airplane to be limited because of loss in lateral-control effectiveness and he considers approach speeds lower than about 120 knots to be dangerous. However, the lateral-control effectiveness was generally found to be adequate at the lowest speeds of these tests in the relatively smooth air in which the approaches were made.

Field-Carrier Landings

Approaches at a shallow flight-path angle.- The time histories of measurements recorded in the field-carrier landings are presented in figure 13. Measurements recorded during an approach in which the pilot took a wave-off are presented in figure 14. Because the gross weight of the airplane varied from 15,200 to 13,000 pounds as fuel was burned, the recorded airspeeds were corrected to show the airspeed that would have been necessary at the same angle of attack for a weight of 14,830 pounds.

The first and second landing approaches were performed at a speed near the minimum accepted as standard for carrier landings and field-carrier landings under normal conditions. In the subsequent landings the pilot reduced the landing approach speed to the minimum he felt he could tolerate with a reasonable degree of safety for the special conditions of these tests. This group of landings includes the lowest speed approaches made in the investigation. In all the landings, with the exception of the second landing, the pilot was able to maintain a flat approach at a nearly constant altitude of about 20 feet for about 15 seconds preceding the cut signal. The second landing approach was different from the other approaches in that the pilot, in order to pass safely over a moving vehicle at the end of the runway, found it necessary to maintain a higher altitude at first and then descend abruptly.

A discussion of each run in order of presentation in figure 13 is given in the following sections.

Run 1: This approach was made at a speed near the minimum accepted for normal operation. The speed for this run was about the minimum-drag speed (about 120 knots) and the records show that only small movements of the throttle were made for speed control. The angle of attack was well below the angle for neutral stability. The pilot's opinion was that this approach was accomplished with less effort than was required in any of the other approaches presented in this investigation.

Run 2: In this approach, even though the speed and angle-of-attack range were similar to those of the previous approach, the difficulty involved in a more abrupt maneuver is apparent. After the rate of descent was started, the pilot had trouble in flaring. He was not able to control his rate of descent and almost landed short on the runway. The throttle was moved forward from about 39° to near 45° (an increase of thrust demand from 2,800 pounds to 4,000 pounds) and the angle of attack was increased from about 7° to about 12°. After the desired altitude was attained a good approach was made for 8 seconds preceding the cut.

Run 3: This approach was made at a speed several knots below the speed for minimum drag. The static margin was less than for the previous approaches and the airplane was at times statically unstable. The pilot attained his desired speed at about 15 seconds before cut and, although he attempted to hold constant speed and altitude, the speed in the last 10 seconds fell to about 103 knots at the cut. As the speed decreased the throttle was moved forward in an effort to control the speed decrease. This indicates that speed control was not possible at a constant throttle setting. From -10 seconds to -7 seconds the speed decreased from 112 to 106 knots and the angle of attack was increased from 12° to about 14° in order to maintain altitude constant as the throttle was moved forward to decrease the deceleration. Flight-path control was unsatisfactory to the pilot. The last 3 seconds preceding the cut show the speed divergence at constant power. The speed decreased from 107 to 103 knots and the angle of attack was increased from 13° to 16°. The pilot considers this deceleration to be excessive and very dangerous in carrier operation.

Run 4: This approach was also made at speeds below the speed for minimum drag and the static margin was very small, or negative, over most of the approach. The pilot found altitude and speed control very difficult and moved the throttle frequently in an attempt to control the speed while holding altitude constant. The oscillations in angle of attack resulting from elevator movement were apparently an attempt to hold the lift constant as speed changes occurred. The elevator movements just before the cut in this approach and in the preceding approach were of greater frequency and amplitude than in the first two landing approaches at the higher approach speed.

Run 5: The speed of the airplane for this approach was about the same as for the previous approach. The static stability, in general, was also similar although the airplane was slightly more unstable for a very short time during this run. The pilot considered altitude and speed control to be extremely difficult and bordering on the impossible. The oscillations in airspeed and the frequent throttle movements show the difficulty of speed control. Angle-of-attack variations were made to hold lift constant as speed changed. Starting at about 7 seconds before the cut the pilot apparently had difficulty maintaining the proper phasing with the airplane response. This resulted in oscillations in the angle of attack between 12° and 15° and deviations in normal acceleration greater than previously encountered. Frequent adjustments and a large amount of throttle movement were made in an effort to maintain constant speed for the last 6 seconds. Control of speed was made more difficult by the lag in engine thrust response. (See fig. 5(a).)

Run 6: In this approach the speed was slightly higher than for the previous approach and the airplane had a little more stability. However, the static margin was very small and the airplane oscillated into the unstable range shortly before the cut. Frequent movements of the throttle were used for speed control and flaperon motions for lateral control were large. The pilot's comments were about the same as for the previous approach.

These six runs can be grouped to indicate three levels of piloting difficulty. The first two runs represent satisfactory conditions; however, it was very difficult to accomplish large and rapid changes in altitude as indicated in run 2.

The third and sixth runs were made under conditions that are unsatisfactory and require a higher than normal level of skill to maintain constant altitude and speed. The difficulty is related to the small static margin, where the angle of attack was close to the neutral point, and to the low airspeed in the approaches.

The fourth and fifth runs were made under conditions which are unacceptable and at times are very dangerous. The static margin is very small during the approach and at times the airplane is in the unstable region. The approach speeds were also below the speed for minimum drag.

The pilot's opinion was that carrier-type approaches at equivalent speeds less than 120 knots should not be considered as safe approach speeds. At the lowest speeds the pilot felt that although he was able to change angle of attack he was not able to change appreciably flight-path angle.

Even though the lateral control in these approaches was generally considered adequate when the air was very calm, brief encounters with turbulence in the approaches caused the pilot great concern and resulted in his use of large control deflections. Visibility over the nose was unsatisfactory at the highest attitude angles, especially when the condition was aggravated by the necessity of "crabbing" the airplane toward the landing-signal officer for a crosswind landing. The pilot was sometimes concerned about striking the ground with the tail skid.

Stall warning in the form of buffeting was not encountered in any of the approaches. Other tests indicated that buffeting would have occurred at speeds lower than those at which the airplane was flown in the approach.

Wave-off following a missed approach.- The time histories of measurements recorded during a low-speed approach and wave-off maneuver are shown in figure 14. The speed was considerably below that for minimum drag and the airplane generally had a very small amount of static stability or was unstable. The pilot felt that altitude control was very poor and speed control was very difficult. Large throttle movements were made in an attempt to maintain constant speed. The landing-signal officer observed the airplane settling nose-high and gave a come-on signal during the approach. This occurred at the time of about 6 seconds, and a large throttle movement was used to check the decay in speed and settling of the airplane along the flight path. The pilot took a wave-off on this pass because the airplane was not steady in speed, altitude, or attitude. The decision to wave off was made at about 19 seconds in the recorded portion of the run. The pilot considered the engine response to be much too slow and he thought the response was inadequate to give him a sufficient increase in altitude to clear a 15-foot Davis-type barrier.

Statistical study of elevator and throttle movements.- The elevator and throttle motions for a considerable number of field-carrier landings made with two different engines installed in the airplane have been analyzed statistically for the last 20 seconds before throttle cut and the results are presented in figures 15 and 16. Data for the throttle motions for the last 5 seconds before cut are not included because few were made during this time interval. In the last 5 seconds the pilot apparently realized he was approaching the position for cut and there would be insufficient time for the airplane to respond to throttle manipulation before he received a cut or wave-off signal. Data from field-carrier landings made in the normal manner with the J48-P-8 engine installed in the airplane and with the J33-A-16A engine installation were included in the statistical analysis with the data made under the special conditions previously described. The data for both engines were grouped because no significant difference was found in the throttle motions for the two different engines. Although no consistent difference could be found in the data, the pilot had a definite preference for the faster accelerating J48-P-8 engine.

The rapid increase in the rate of elevator and throttle movement with angle of attack for the approach maneuvers is apparent (figs. 15 and 16). The number of throttle changes per second also increased rapidly with angle of attack. The large increase of motions used by the pilot for both the elevator and engine controls substantiates the pilot's opinion of the poor flying qualities at low speeds and is indicative of the increased work the pilot performs at the low speeds.

Analog Simulation of Airplane and Hypothetical Autopilot in High-Dip Maneuver at Constant Thrust

A check to determine how well the airplane in the approach condition was simulated by the analog computer (without autopilot) was made by comparing the output of the analog computer with the actual recorded motions of the airplane in a flight maneuver. The comparison was made by using a step input to the analog computer as an approximate representation of the elevator-deflection time history obtained in a pull-up maneuver. The results, shown in figure 17, indicate that the airplane was reasonably simulated by the analog computer in a rapid pull-up maneuver.

The ability of a hypothetical autopilot-airplane combination to follow a desired variation of altitude is demonstrated in the output of the analog computer shown in figure 18. The input task for the autopilot was a maneuver requiring an altitude loss of 15 feet in a flight-path distance of 1,200 feet, as shown in figure 4; the time required for the maneuver therefore varied inversely with approach speed. The initial thrust was held constant throughout the maneuvers. The output time histories of altitude, attitude angle, angle of attack, elevator angle, and airspeed are presented for the maneuvers starting from trimmed flight at three different airspeeds.

The results indicate (fig. 18) that the autopilot performed the altitude change required in the initial part of the maneuver for all three approach speeds, 145 knots, 109 knots, and 102 knots, and used about the same amount of elevator deflection for each speed. However, the autopilot did not adequately control the speed and altitude in the latter part of the maneuver at 109 and 102 knots. The frequency of elevator motion was less at the low speeds since more time was available to complete the maneuver. The motions of the airplane appear to be adequately damped at all three speeds. Gain settings were kept constant for all speeds. The angle-of-attack range for the two lower approach speeds was sufficiently high so that the airplane had a negative static margin and, at the lowest approach speed, the angle of attack went as high as 18°. Although the automatic pilot was apparently able to control an unstable airplane for a specific set of conditions, this is no indication that the pilot would be willing to accept any considerable amount of instability in the landing approach. While making low-speed field-carrier landings the pilot preferred to fly in the angle-of-attack range where the airplane was stable with a small margin allowed for maneuvering the airplane. Occasionally the pilot increased the angle to the unstable range but only just prior to touchdown and considered the flying qualities of the airplane unsatisfactory in the unstable angle-of-attack range.

The autopilot held the altitude nearly constant after completing the initial altitude change required at 145 knots but was unable to control altitude with the same gain settings at 109 and 102 knots. The speed and altitude diverged continuously after the initial altitude change was completed in the maneuvers starting at 109 knots and 102 knots. This divergence has been shown to result from the manner in which drag varies with speed (fig. 7) and was demonstrated in flight (fig. 8). The autopilot did not have thrust control and operated at a constant gain setting for elevator control; therefore, the speed and altitude could not be kept constant. The pilot of the test airplane in actual approach maneuvers had difficulty in controlling speed and altitude at speeds below 120 knots (the speed for minimum drag) even though thrust control was available. The need for frequent thrust adjustment imposes an additional task on the pilot and, therefore, approaches at speeds below the speed for minimum drag are difficult.

CONCLUDING REMARKS

Flight tests have indicated several factors which influence the pilot's selection of minimum speeds while flying a carrier-type landing approach in the Grumman F9F-7 airplane. The relative importance of these factors and the order of their occurrence are difficult to determine. Some of these factors occur abruptly whereas others steadily increase the difficulty of control as speed is decreased over a fairly large speed range. The factors influencing the approach speed of the test airplane are listed in an approximate order of occurrence as the approach speed is reduced:

1. Lateral-control effectiveness has been shown to decrease rather abruptly and, in the opinion of the pilot, limits the minimum approach speed in rough air to approximately 120 knots at 14,830 pounds gross weight (2,500 pounds fuel). This factor is of secondary importance in flight in calm air during which very little lateral control is necessary.

2. Control of airspeed while flight-path angle is held constant or control of height while airspeed is held constant becomes increasingly difficult as the approach speed is decreased below the speed for minimum drag. This lack of stability under constraint was demonstrated by flight maneuvers, drag variations with airspeed, and analog-computer studies.

3. Approaches must be made at an angle of attack less than the angle of attack at which control difficulty is experienced in order to allow some margin for maneuvering the airplane. This allowance for maneuvering must be made regardless of the cause of the difficulty and results in an increased approach speed. In these tests, the pilot made approaches with a smaller margin for maneuvering than would be considered safe for usual field-carrier landings.

4. The static margin decreased abruptly at high angles of attack and the airplane became statically unstable. The pilot felt this instability was serious and caused him considerable difficulty in the landing approach. The center of gravity of the airplane moved rearward as fuel was used and resulted in decreased static margins for a specific angle of attack.

5. The engine thrust response of the Allison J33-A-16A engine was comparatively slow. The Pratt & Whitney J48-P-8 engine provided a significant improvement but the pilot considered the thrust response inadequate for proper speed control below 120 knots. Consideration of the airplane's poor wave-off performance at low speeds probably had some influence on the pilot's approach speed.

6. Visibility over the nose of the airplane was inadequate at the lowest speeds of these tests. Consideration of visibility requirements is believed to be very important, especially in the design of airplanes having low-aspect-ratio and swept-back wings.

7. Touchdown restrictions by the landing-gear configuration were considered objectionable for this airplane and the tail skid made first contact a few times. Although carrier landings are generally made with a slight decrease in attitude angle after the cut, the decrease does not always prevent striking the tail skid first and damage may result if the landing is made at a high rate of sink.

8. Stall warning, such as buffeting or abrupt wing drop, was not encountered in the approaches made in these tests. However, a stall warning encountered in approaches in a different airplane configuration

might have an important influence and would possibly limit the approach speed.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., May 23, 1957.

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3. White, Maurice D., and Drinkwater, Fred J., III: A Comparison of Carrier Approach Speeds As Determined From Flight Test and From Pilot-Operated Simulator Studies. NACA RM A57D30, 1957.

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5. Zalovcik, John A., Lina, Lindsay J., and Trant, James P., Jr.: A Method of Calibrating Airspeed Installations on Airplanes at Transonic and Supersonic Speeds by the Use of Accelerometer and Attitude-Angle Measurements. NACA Rep. 1145, 1953. (Supersedes NACA TN 2099 by Zalovcik and NACA TN 2570 by Lina and Trant.)

6. Donegan, James J.: Matrix Methods for Determining the Longitudinal-Stability Derivatives of an Airplane From Transient Flight Data. NACA Rep. 1169, 1954. (Supersedes NACA TN 2902.)

7. Neumark, S.: Problems of Longitudinal Stability Below Minimum Drag Speed, and Theory of Stability Under Constraint. Rep. No. Aero. 2504, British R.A.E., July 1953.

TABLE I

PRINCIPAL DIMENSIONS OF AIRPLANE

General:	
Span, in.	414
Length-flight attitude, in.	492.75
Height, in.	147.5
Empty weight, lb	12,330
Weight at take-off, lb	18,304
Design gross weight including external stores (catapulting), lb	20,516
Moment of inertia in pitch, slug-ft^2	26,676
Wings:	
Type	Midwing
Airfoil section	NACA 64A010
Chord at airplane center line, in.	138
Chord at tip, in.	69
Incidence, deg	0
Dihedral, deg	0
Sweepback at 1/4 chord, deg	35
Aspect ratio	4
Stabilizer:	
Span, in.	170
Maximum chord, in.	41
Incidence	Variable
Dihedral, deg	0
Area, sq ft:	
Wing	300.00
Wing trimmer, left wing only	2.37
Flaperons	18.50
Flaps, total	60.30
Stabilizer, including elevators	49.56
Elevator, including tabs	12.70
Fin, including rudder	21.52
Rudder, including tab	11.22

TABLE II

AIRPLANE CONTROL-SURFACE MOVEMENT

Control surfaces	Movement	Range, deg
Flaperons	T.E. Up	55
Elevator	T.E. Up T.E. Down	30 15
Stabilizer	L.E. Up L.E. Down	$1\frac{3}{4}$ 6
Wing flaps (inboard)	Down	40
Wing flaps (outboard)	Down	30
Wing lateral trimmer	Up Down	15 15
Rudder	Left Right	25 25
Rudder trim tab (lower)	Left Right	5 5

TABLE III

APPROXIMATE RANGE AND READING ACCURACY

OF RECORDING INSTRUMENTS

Measurement	Range	Reading accuracy
Static pressure, lb/sq ft	0 to 2,200	±2
Impact pressure, lb/sq ft	0 to 250	±0.2
Tail-pipe pressure, lb/sq ft	0 to 2,000	±2
Inlet pressure, lb/sq ft	0 to 100	±0.2
Differential static pressure, lb/sq ft	-50 to 100	±0.15
Normal acceleration, g units	0 to 2	±0.005
Longitudinal acceleration, g units	-1/2 to 1/2	±0.005
Pitching velocity, radians/sec	-1/4 to 1/4	±0.001
Pitching acceleration, radians/sec^2	-1/2 to 1/2	±0.003
Rolling velocity, radians/sec	-1/2 to 1/2	±0.003
Rolling acceleration, radians/sec^2	-0.8 to 0.8	±0.004
Elevator deflection, deg	-30 to 15	±0.2
Flaperon deflection, deg	0 to 57	±0.2
Throttle deflection, deg	0 to 62	±0.2
Stabilizer deflection, deg	-6 to 2	±0.02
Angle of attack, deg	-17 to 34	±0.05
Temperature, $^{\circ}$F	0 to 100	±0.3
Attitude angle, deg	30	±0.1

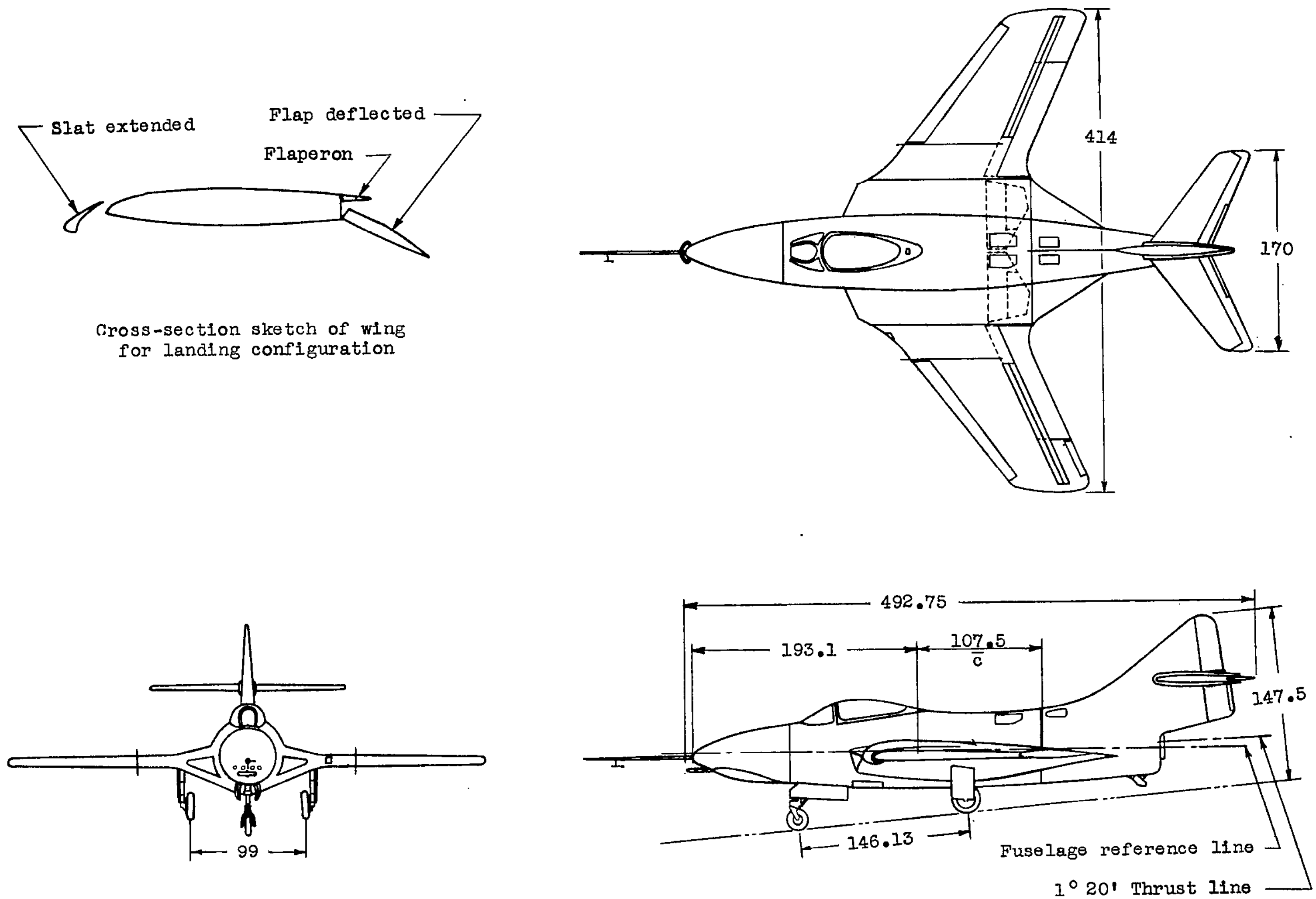
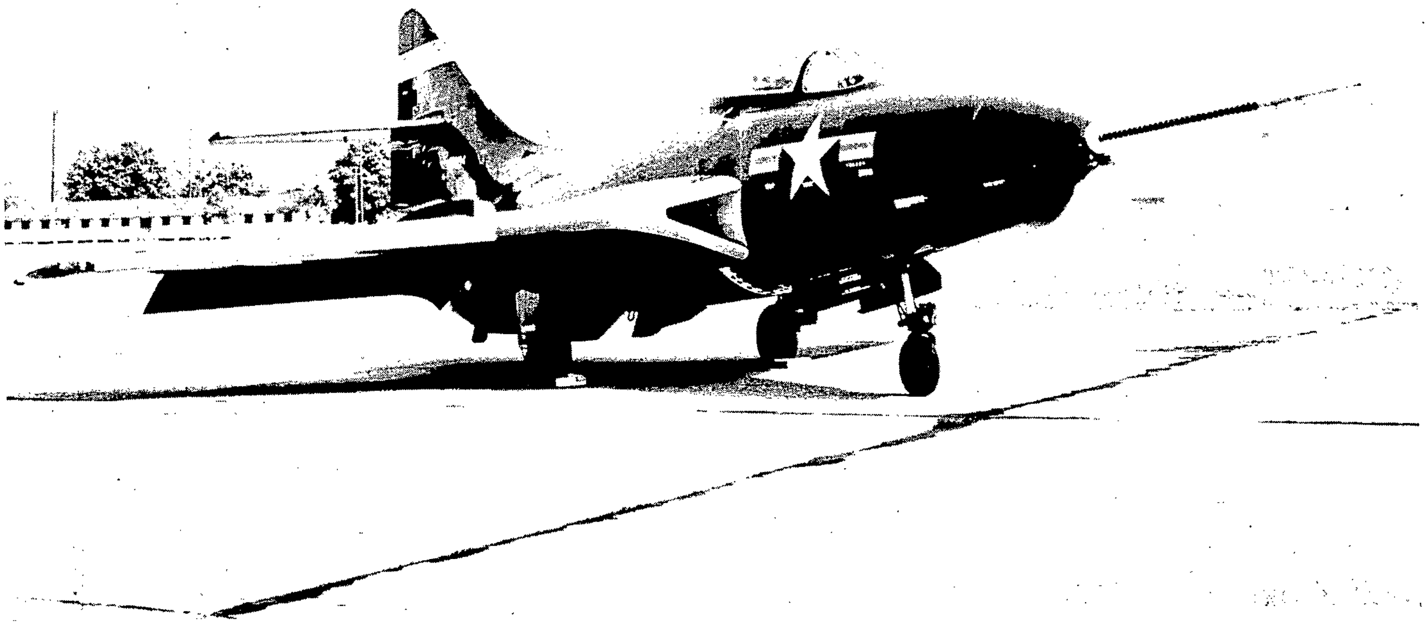
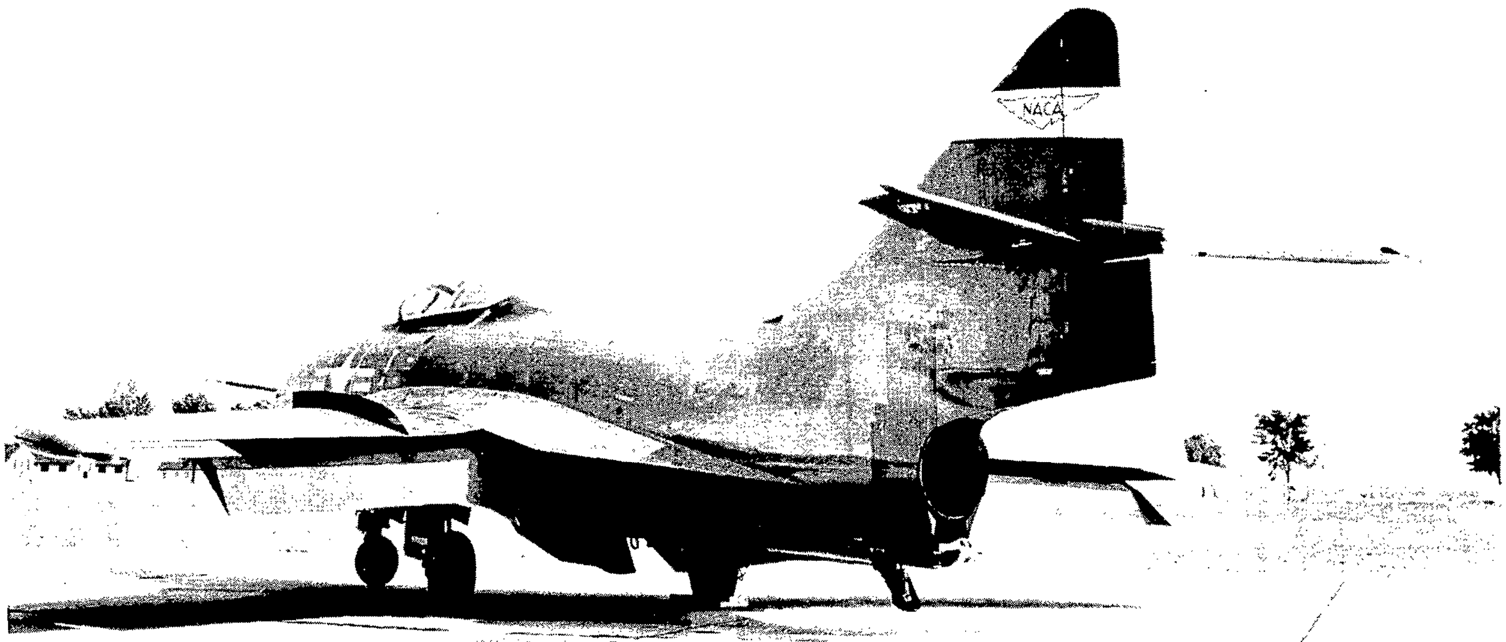


Figure 1.- Three-view drawing of the Grumman F9F-7 airplane and a sketch of the wing cross section showing the slat, flap, and flaperon. (All linear dimensions are in inches.)



(a) Three-quarter front view. L-95264

Figure 2.- Photographs of the F9F-7 airplane.



(b) Three-quarter rear view. L-95265

Figure 2.- Concluded.

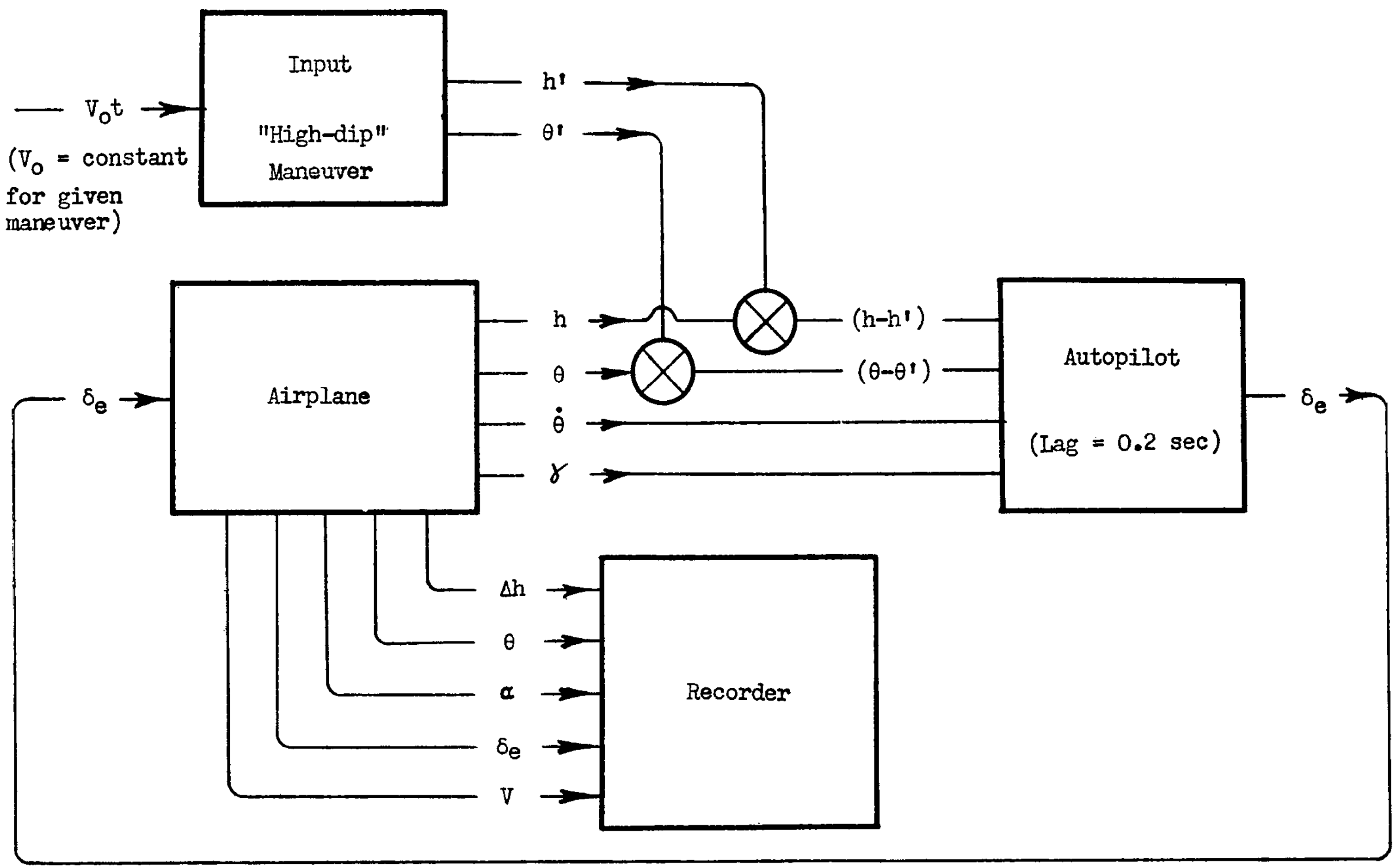


Figure 3.- Block diagram of analog-computer simulation of airplane and autopilot.

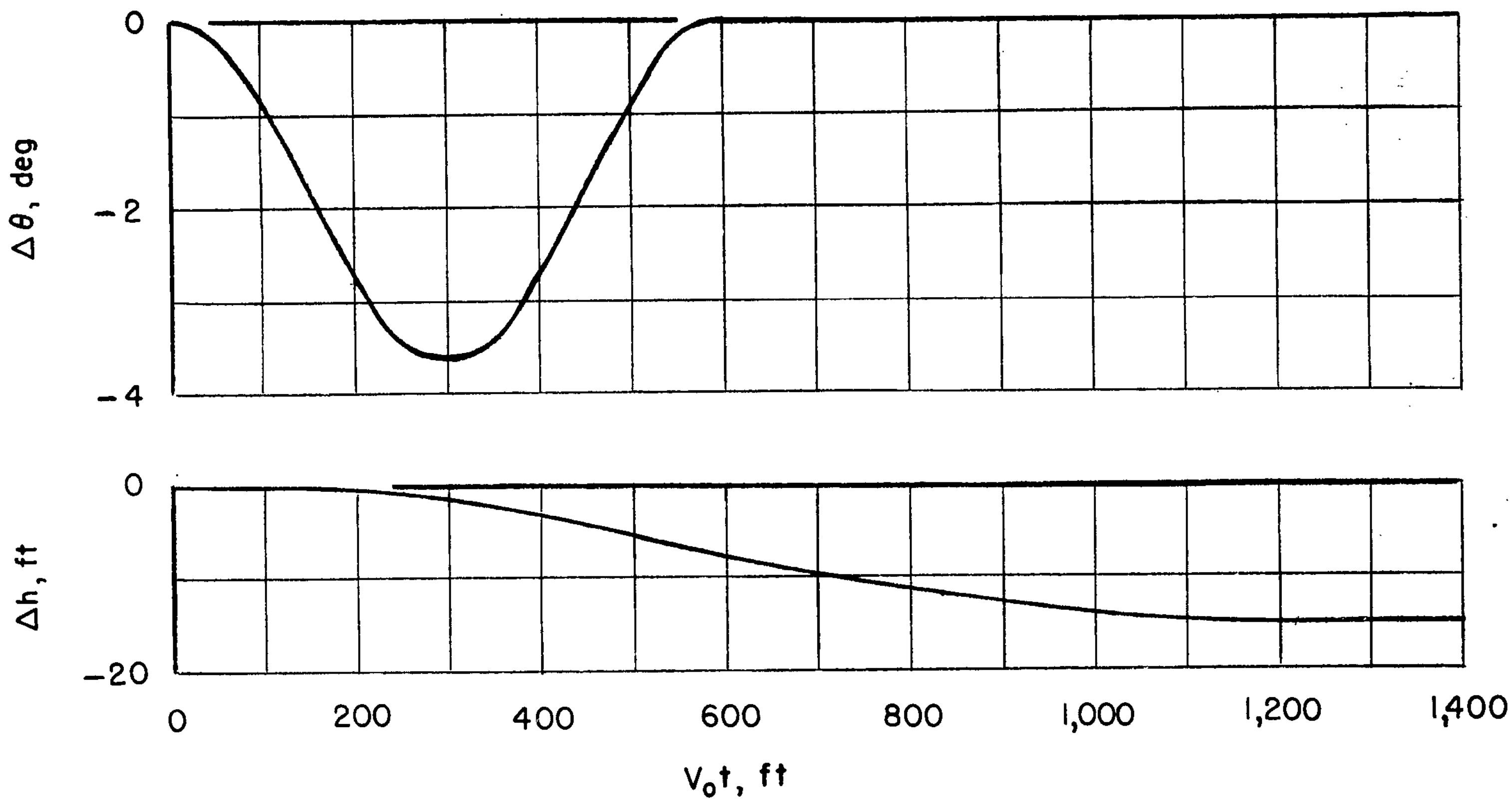
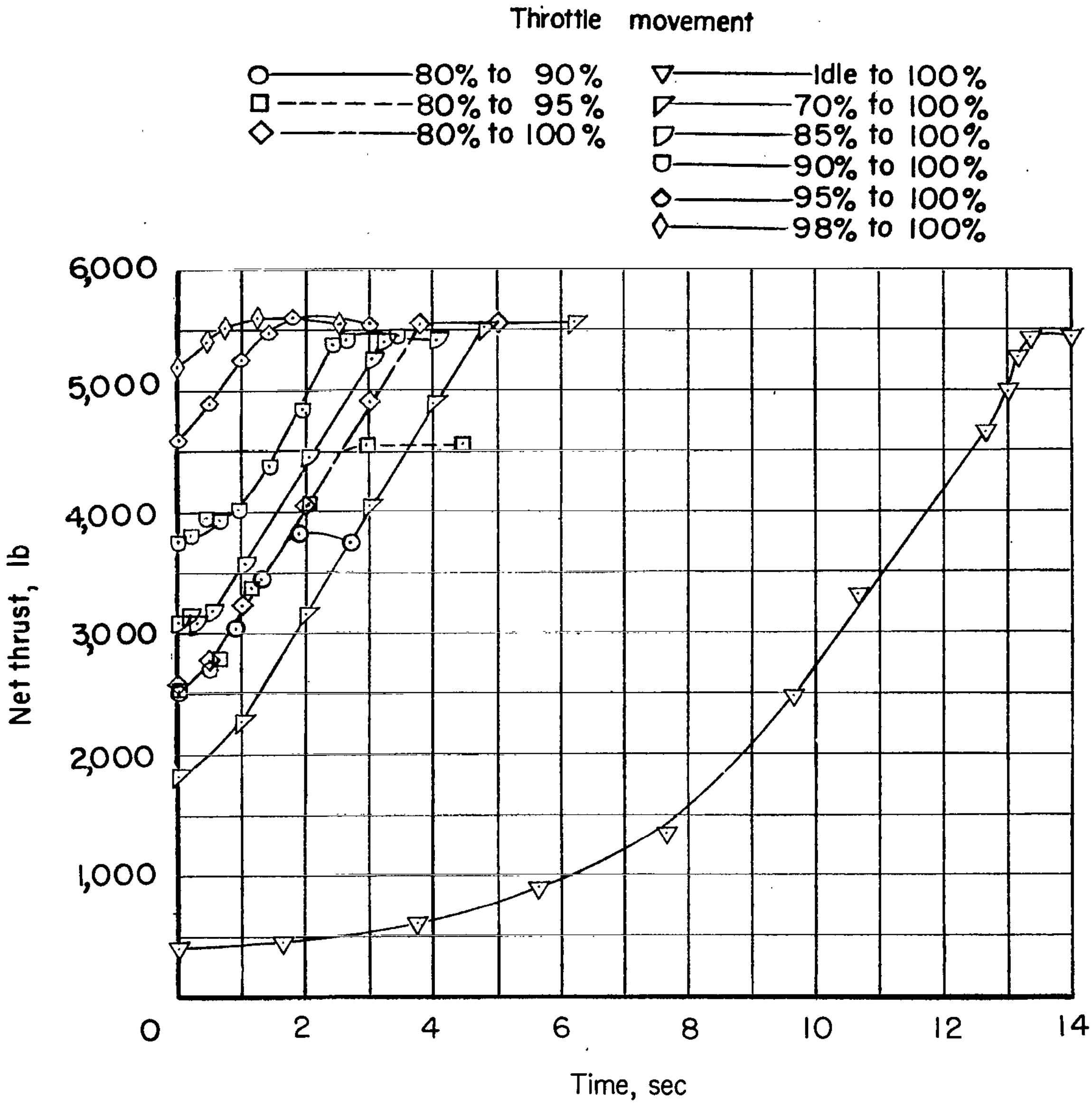
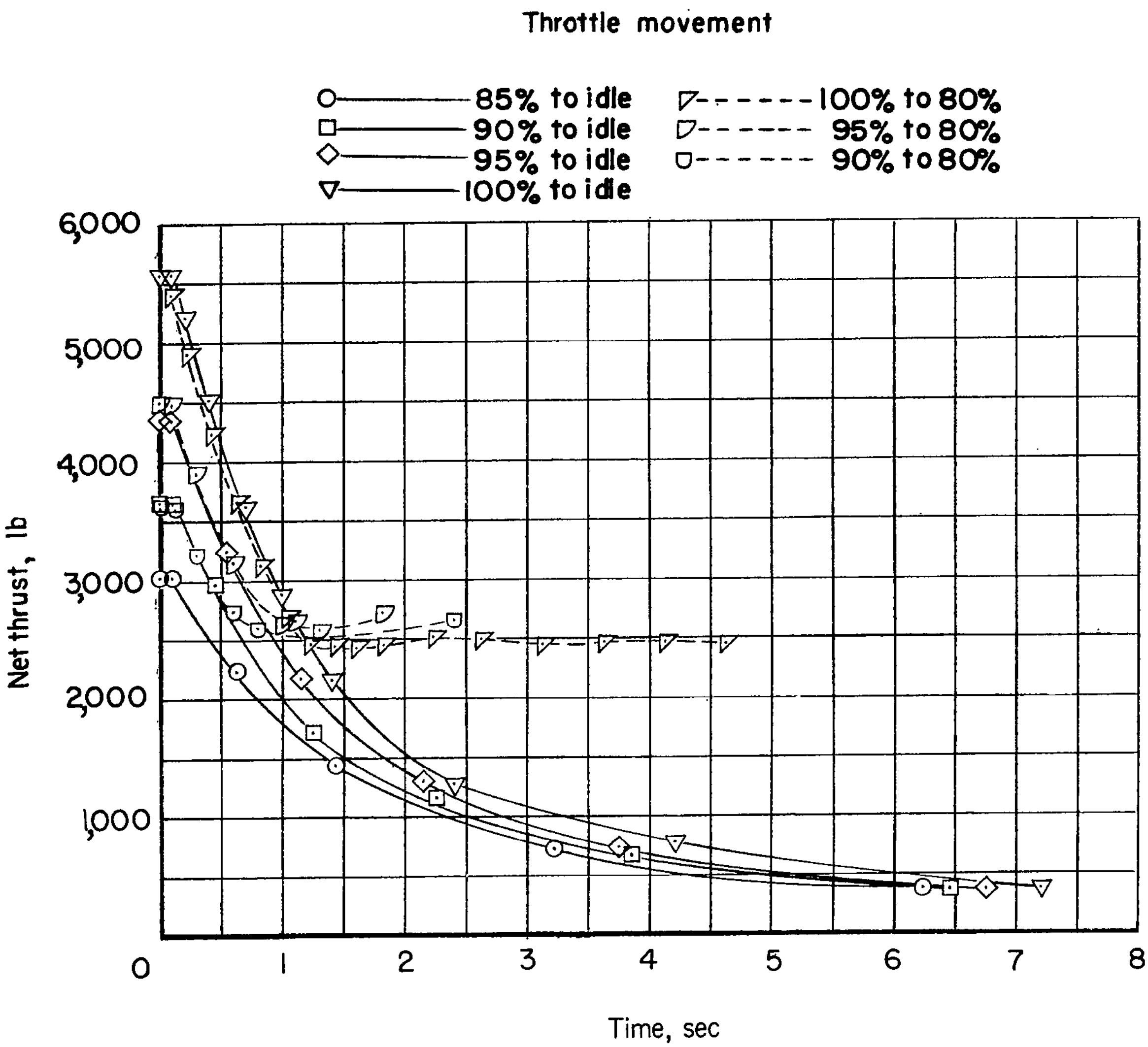


Figure 4.- Desired variation of altitude and attitude angle with distance in the standard "high dip" maneuver used in the analog simulation.



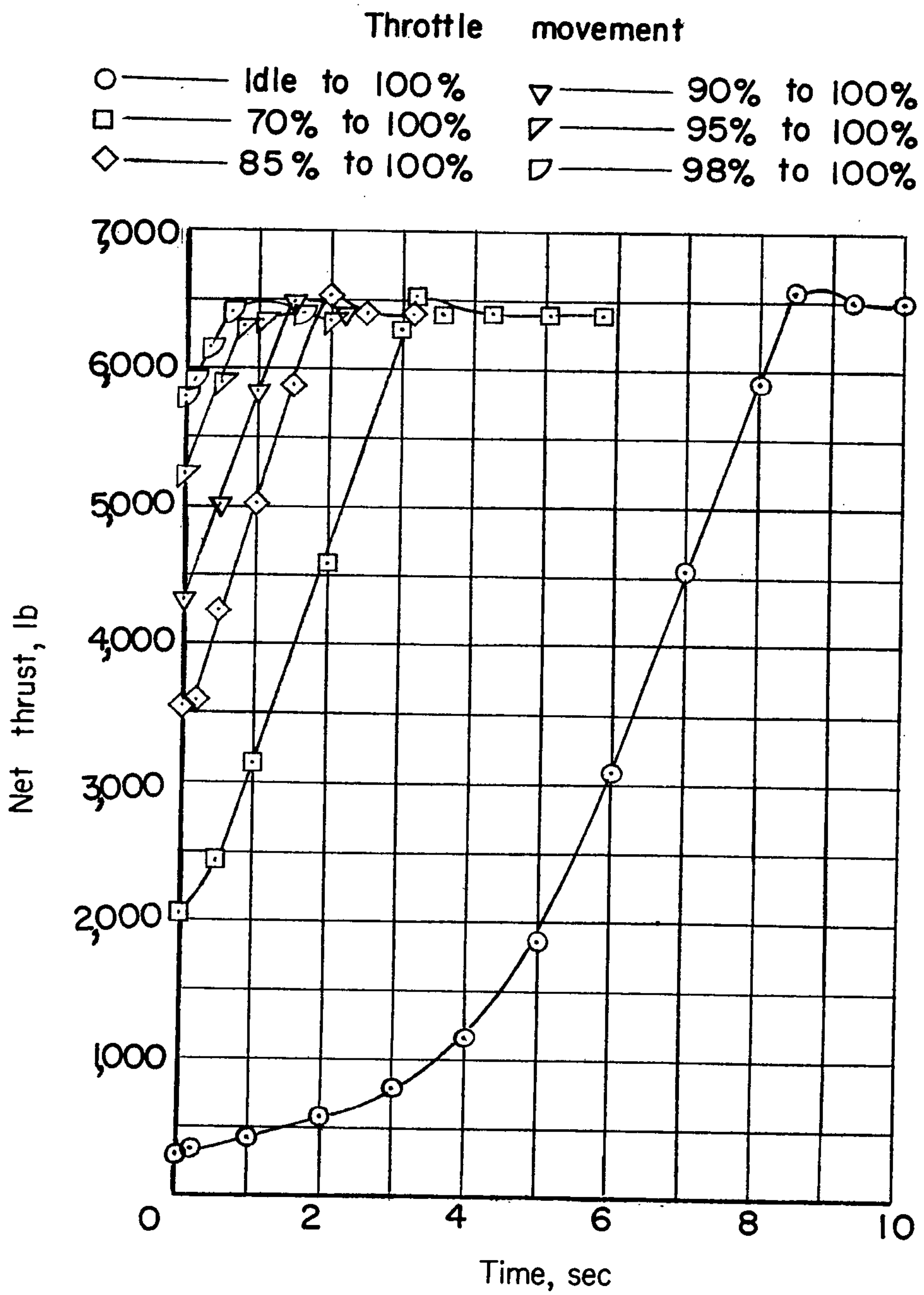
(a) Allison J33-A-16A engine. Increasing thrust; atmospheric temperature, 83° F; atmospheric pressure, 29.69 in. Hg.

Figure 5.- Thrust response of the Allison J33-A-16A and Pratt & Whitney J48-P-8 engines installed in the airplane to step throttle movements.



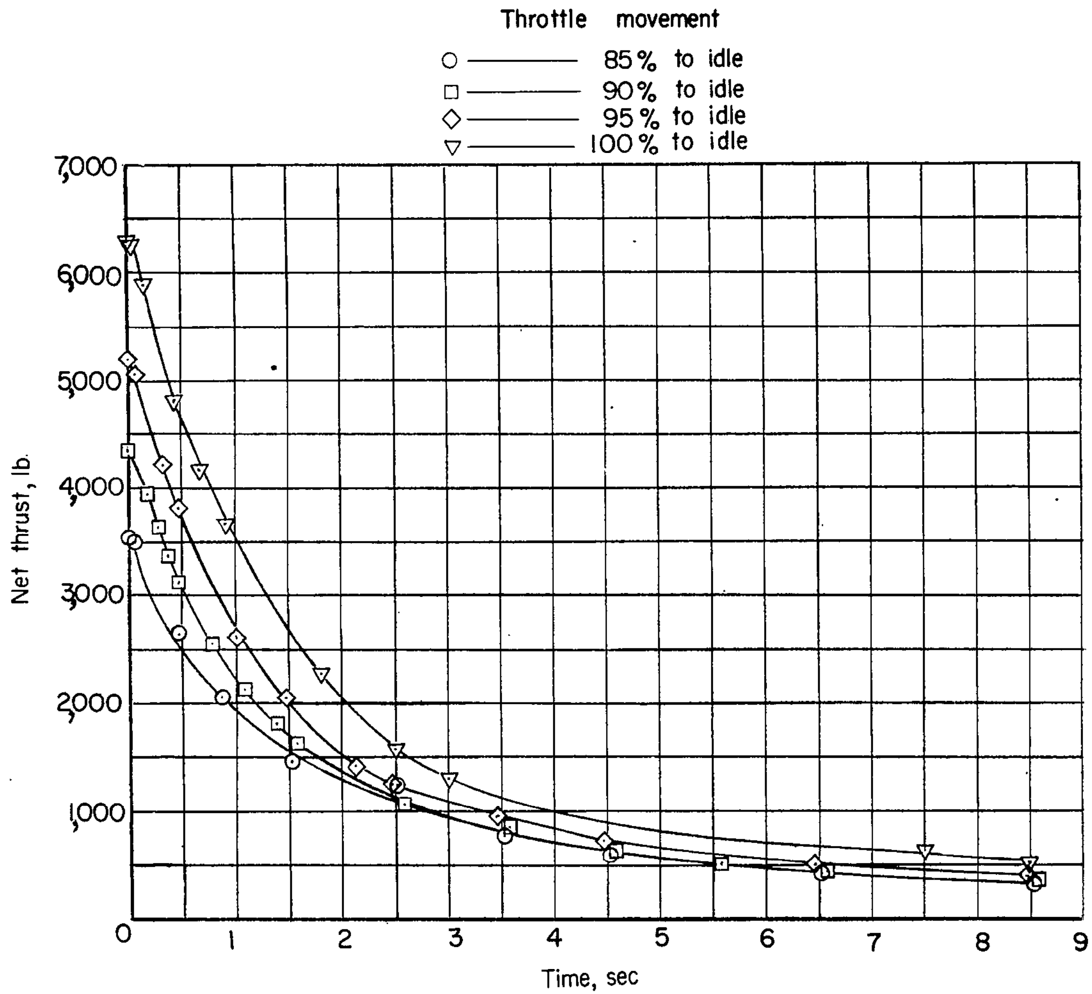
(b) Allison J33-A-16A engine. Decreasing thrust; atmospheric temperature, 83° F; atmospheric pressure, 29.69 in. Hg.

Figure 5.- Continued.



(c) Pratt & Whitney J48-P-8 engine. Increasing thrust; atmospheric temperature, 66° F; atmospheric pressure, 30.16 in. Hg.

Figure 5.- Continued.



(d) Pratt & Whitney J48-P-8 engine. Decreasing thrust; atmospheric temperature, 66° F; atmospheric pressure, 30.16 in. Hg.

Figure 5.- Concluded.

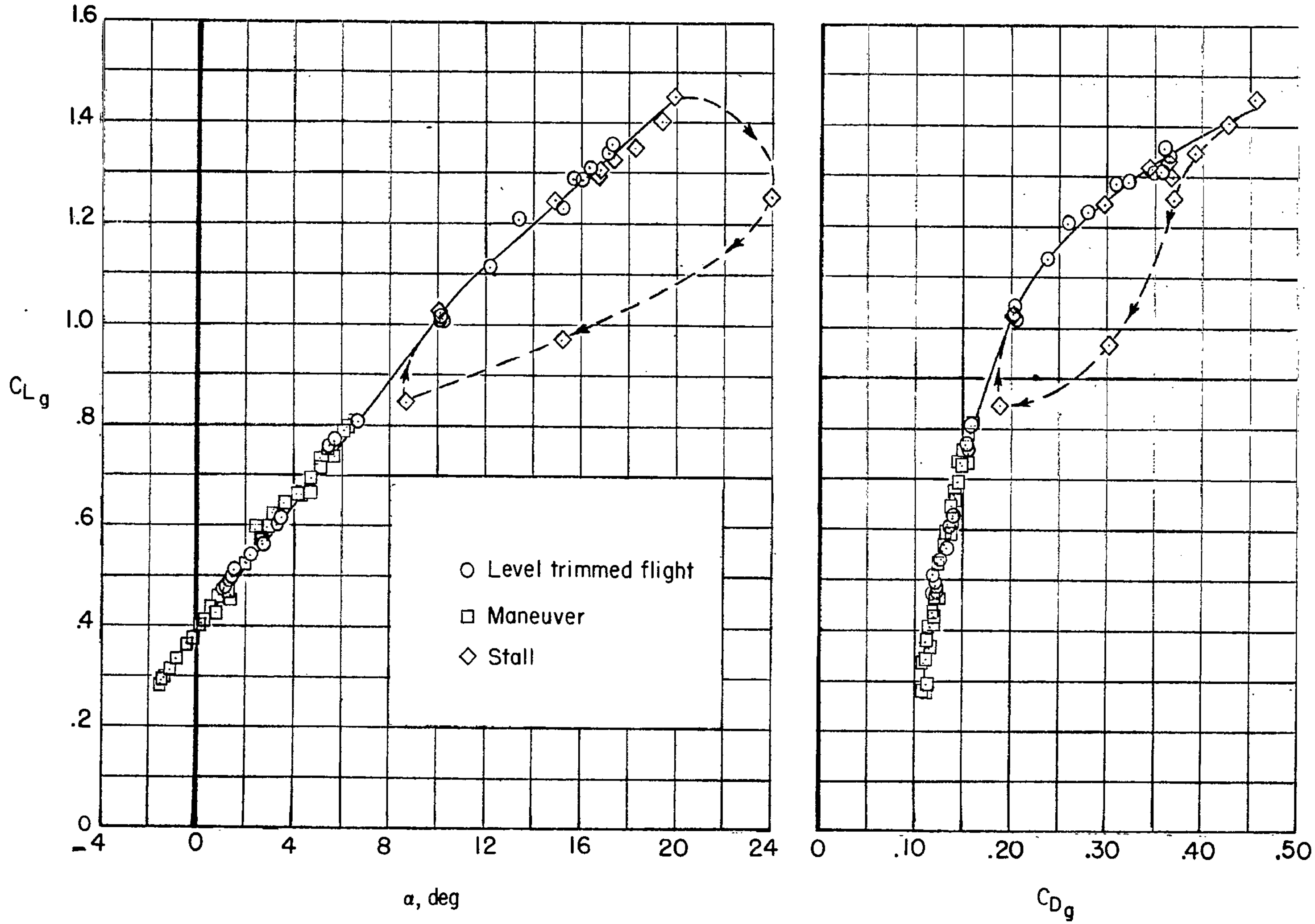
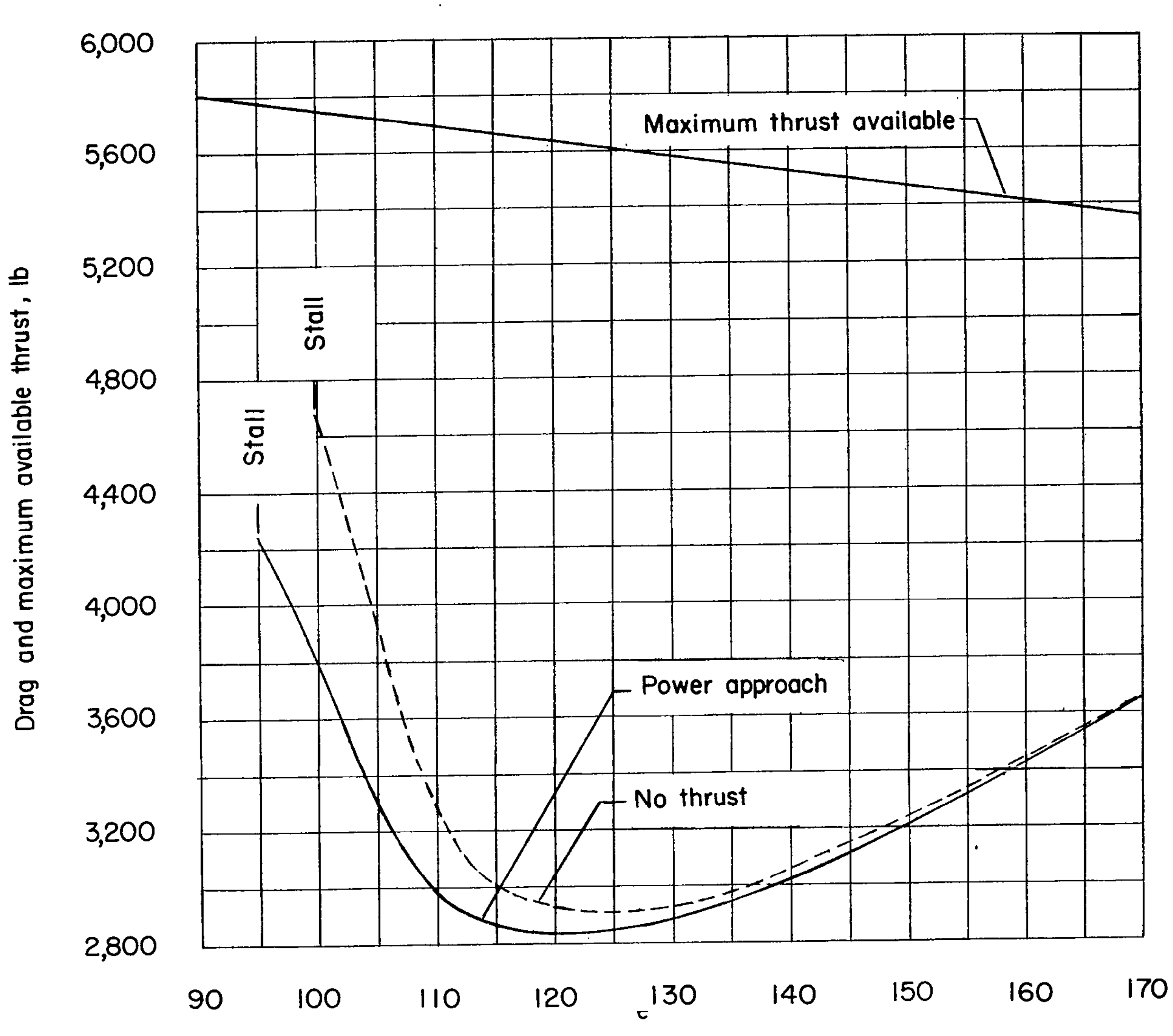


Figure 6.- Gross lift and drag coefficients.


6,000
5,600
5,200
4,800
4,400
4,000
3,600
3,200
2,800
Drag and maximum available thrust, lb
90
100
110
120
130
140
150
160
170
Maximum thrust available
Stall
Stall
Power approach
No thrust

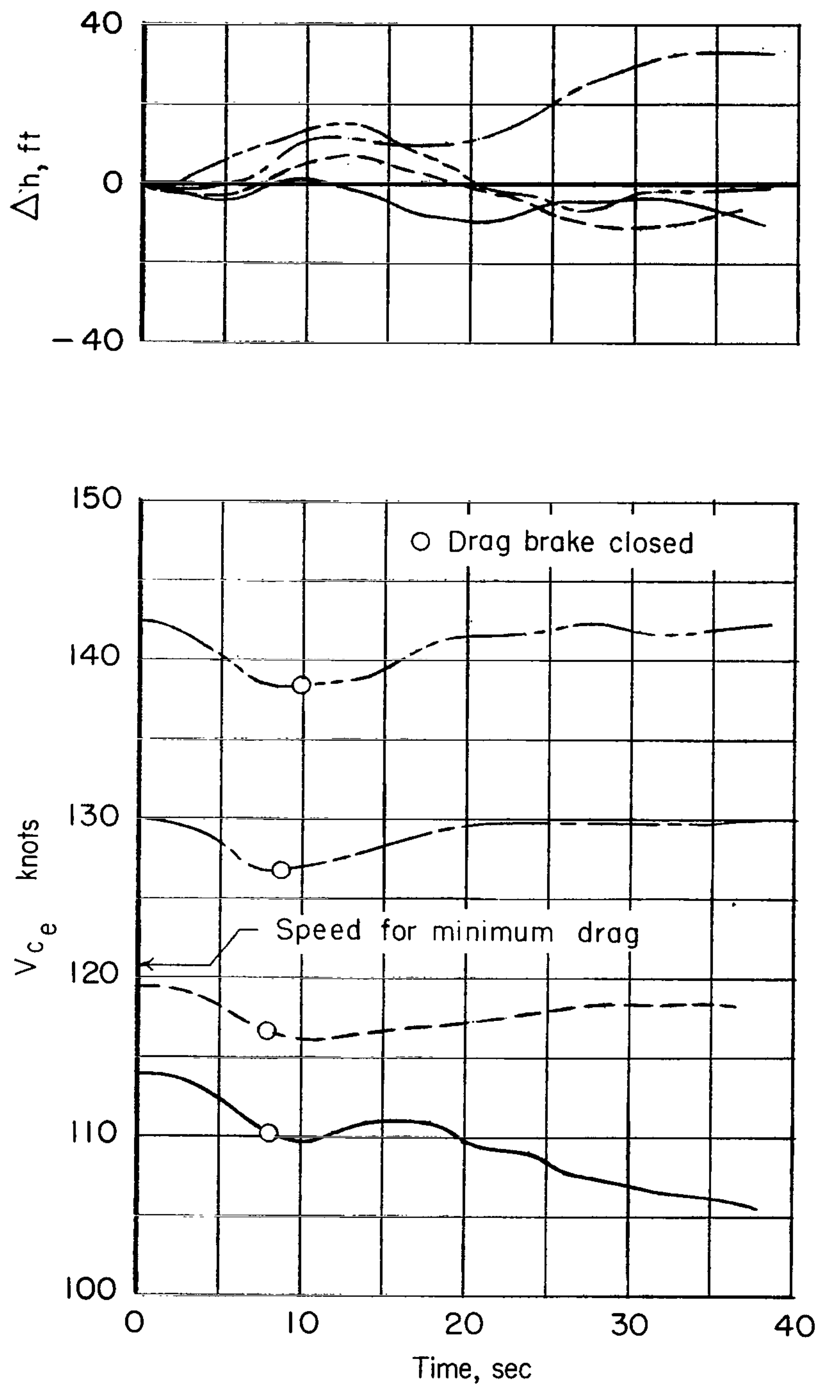
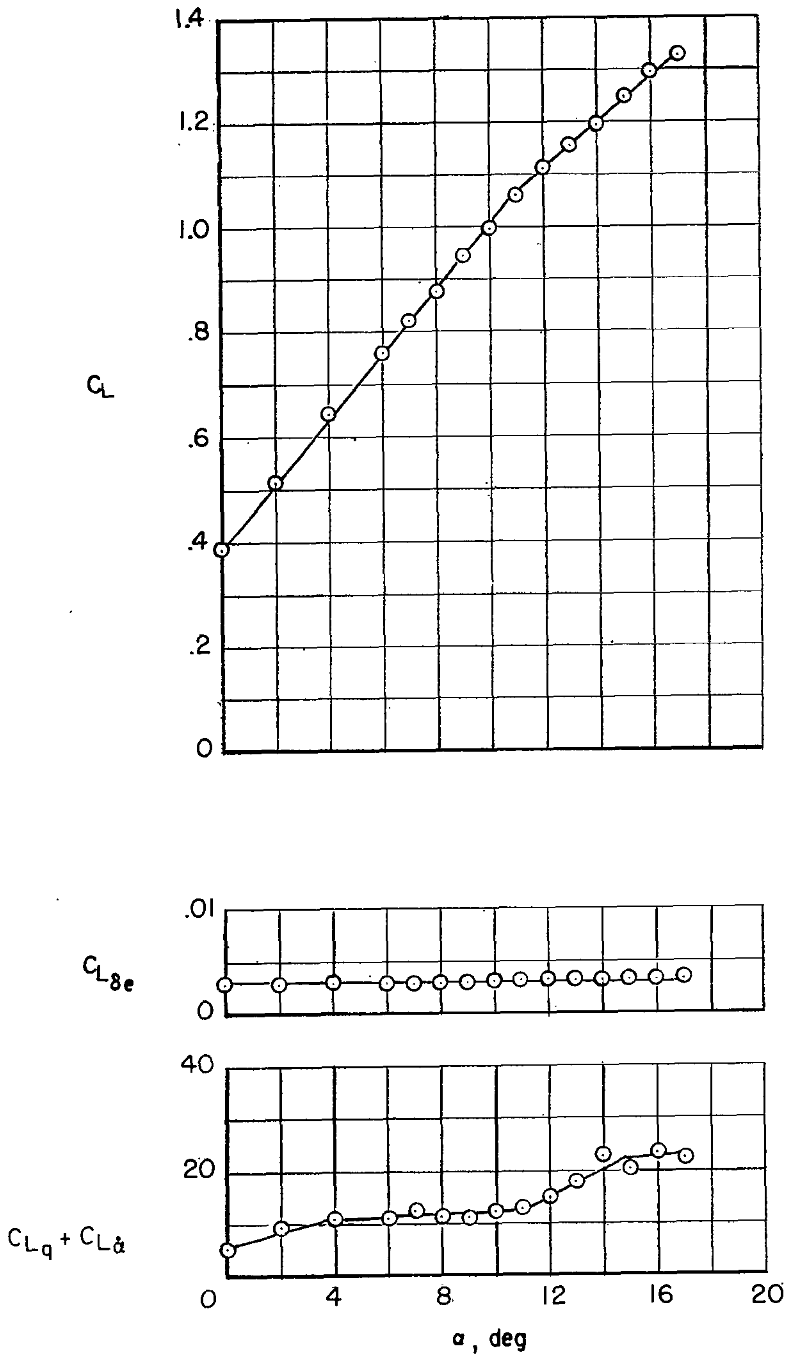
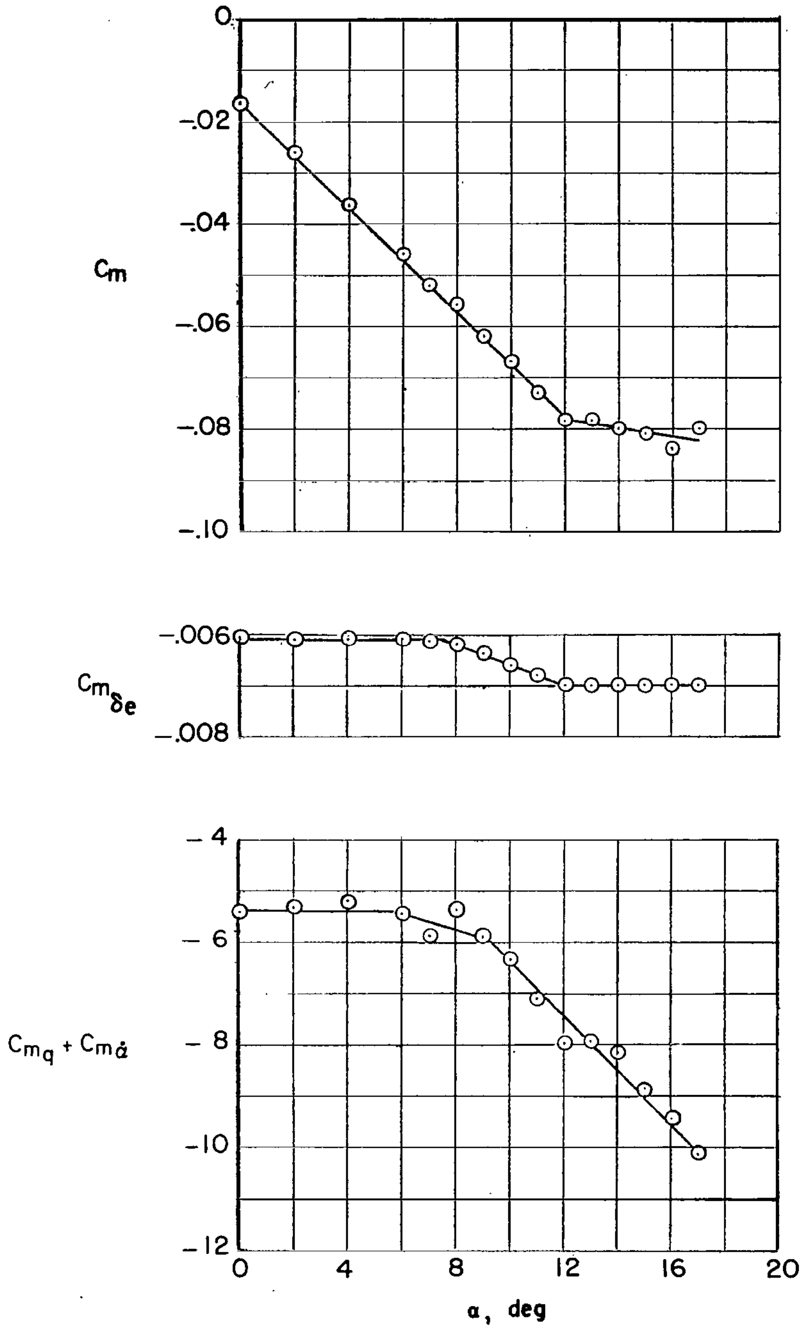


Figure 8.- Speed changes at constant throttle setting and nearly constant altitude following a drag disturbance.



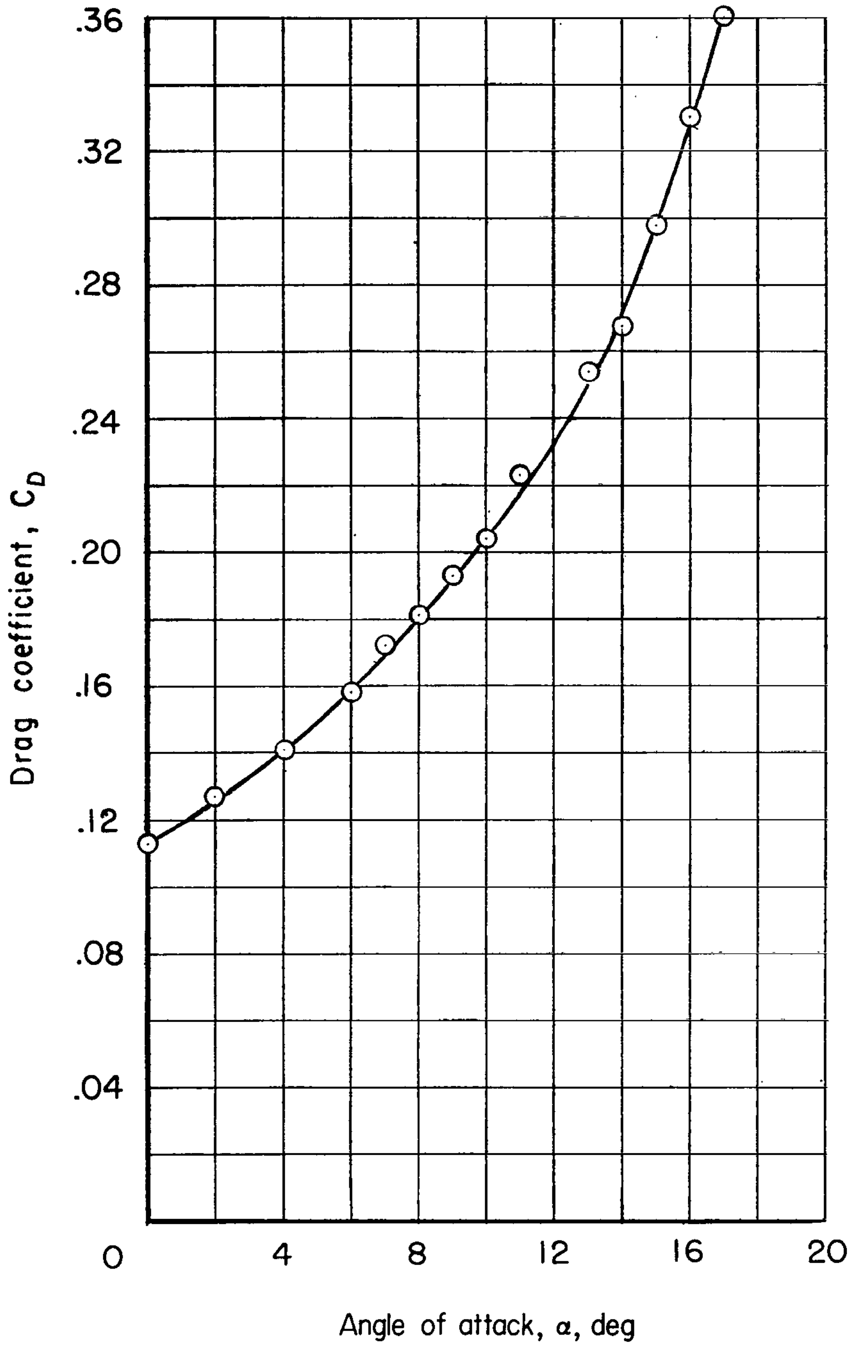
(a) Lift.

Figure 9.- Longitudinal aerodynamic characteristics.



(b) Pitching moment.

Figure 9.- Continued.



(c) Drag.

Figure 9.- Concluded.

[redacted]

Run	Airplane gross weight, lb	Fuel remaining, lb	c.g. location, percent $\bar{c}$
---	12,330	0	30.2
1	15,230	2,900	26.7
2	14,980	2,650	26.9
3	14,630	2,300	27.2
4	13,730	1,400	28.0
5	13,280	950	28.4
6	13,030	700	28.8

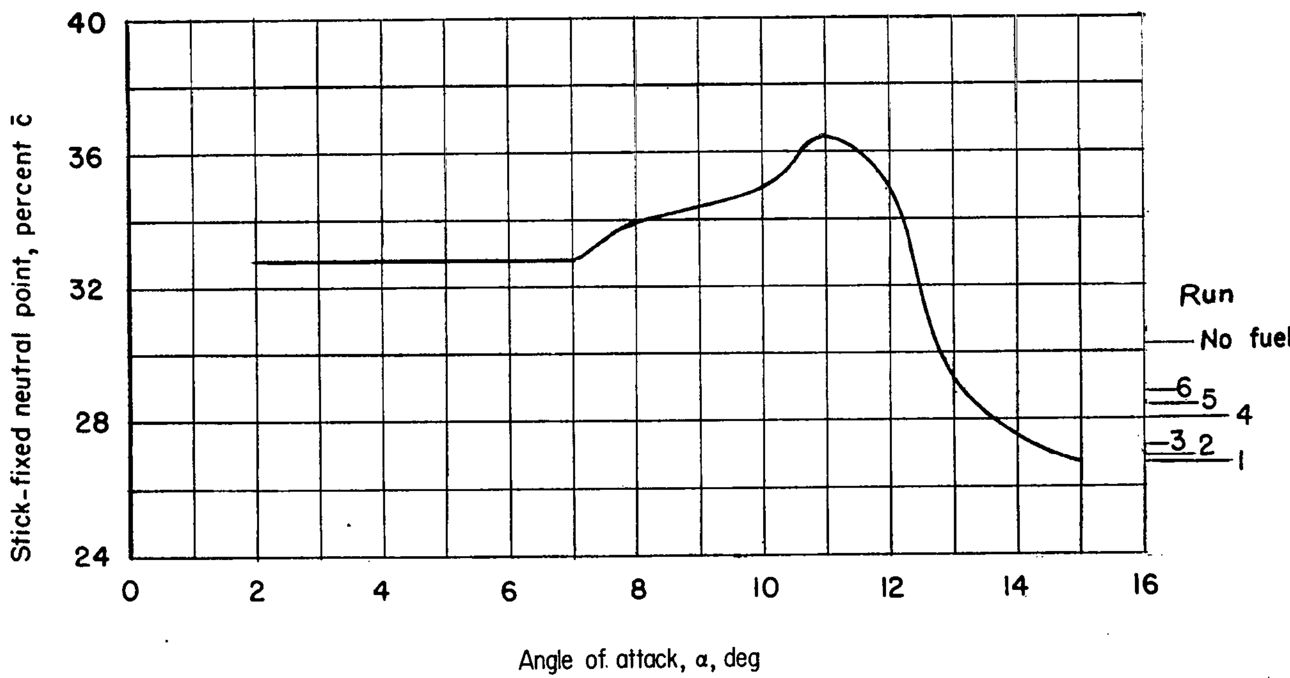


Figure 10.- Variation of location of stick-fixed neutral point with angle of attack.

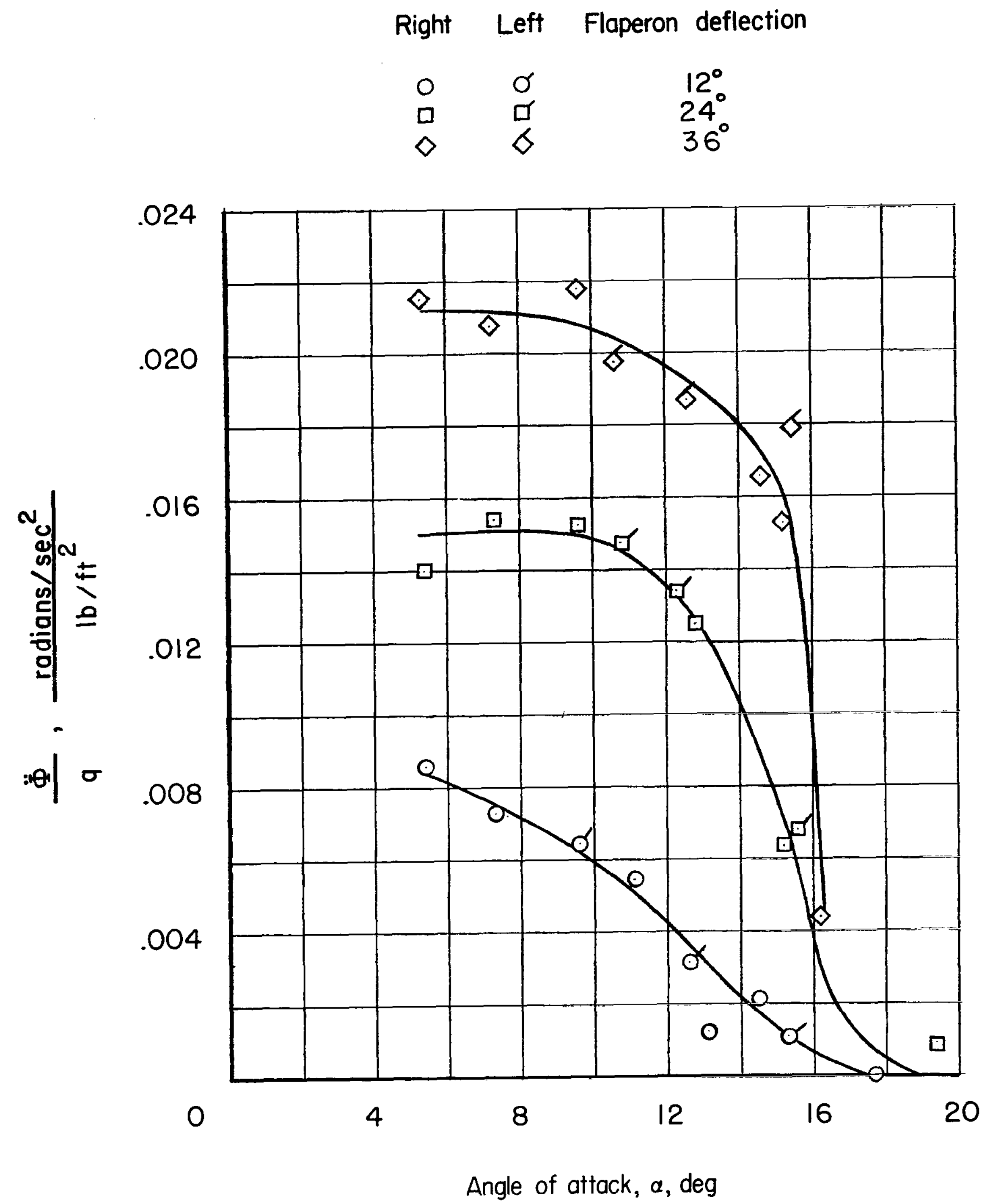


Figure 11.- Variation of flaperon effectiveness with angle of attack.

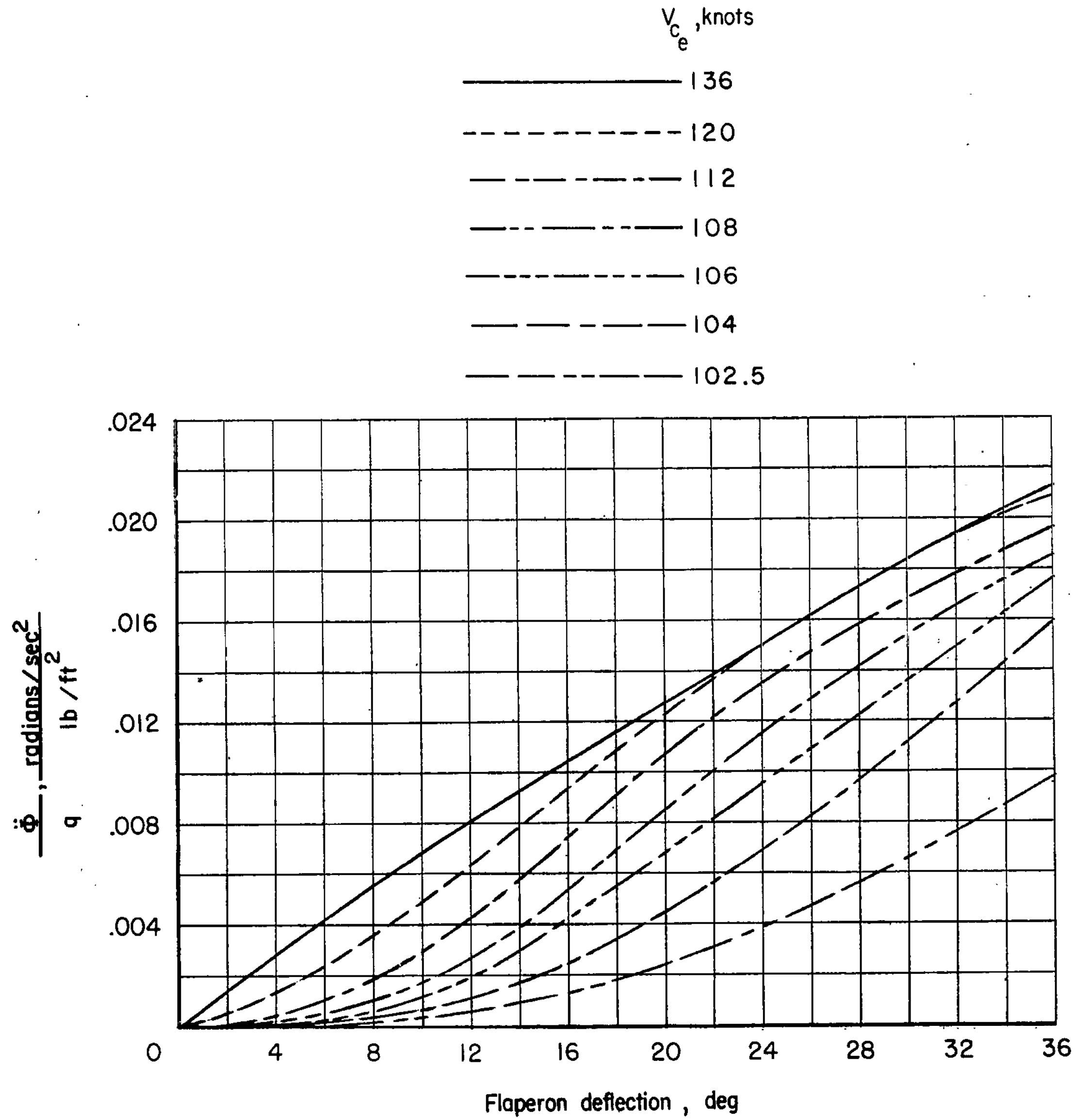
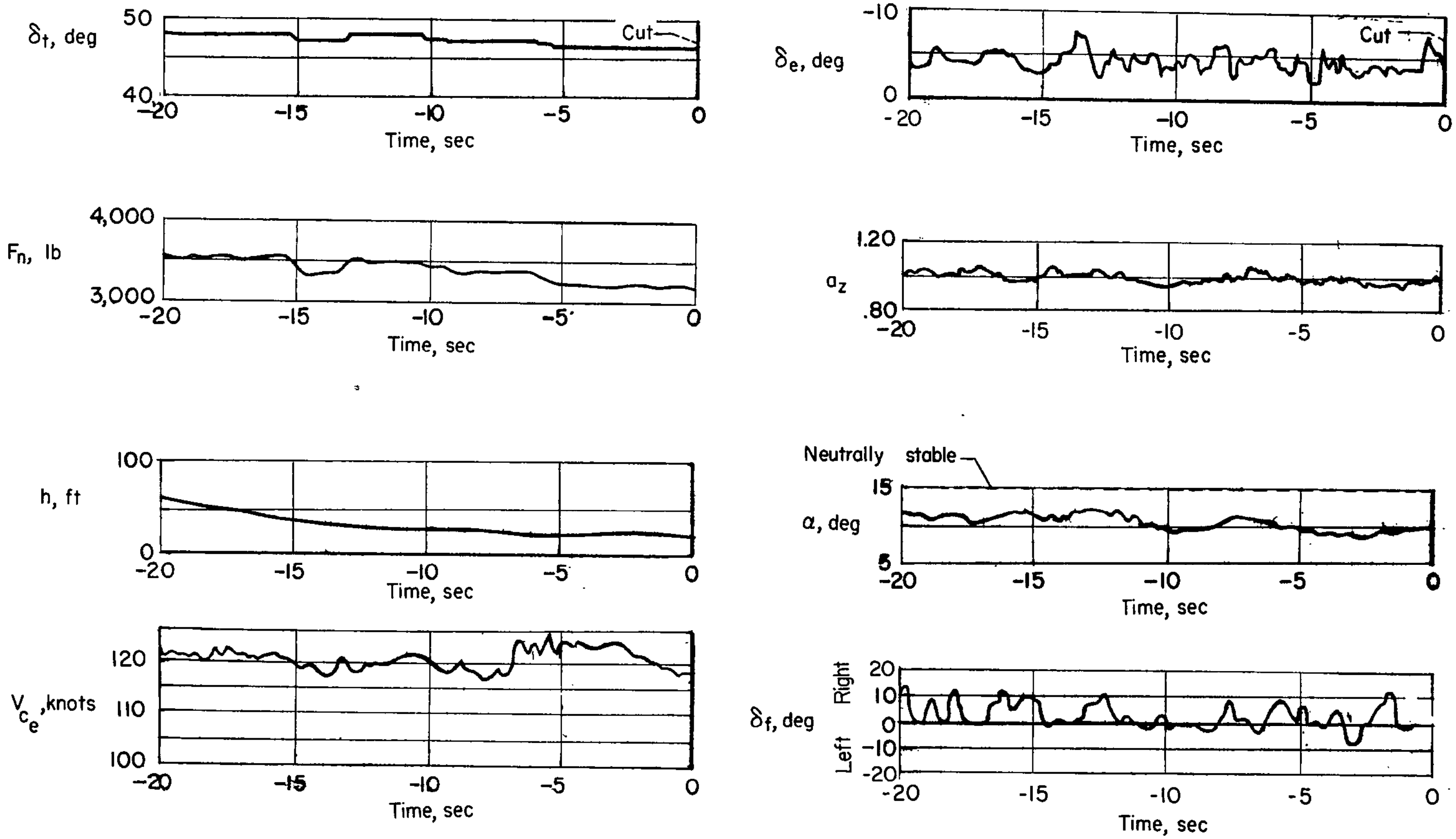
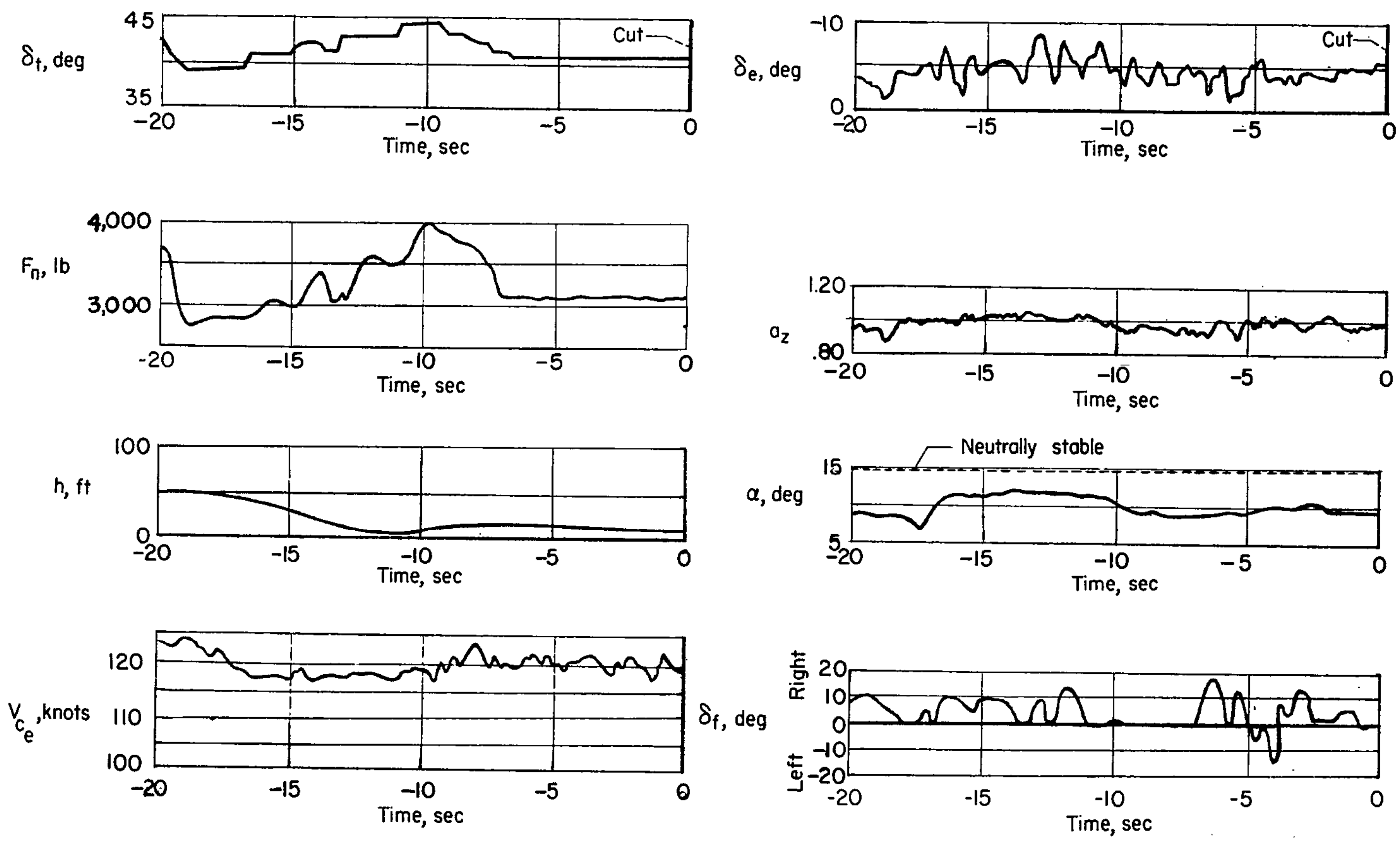


Figure 12.- Variation of flaperon effectiveness with flaperon deflection at various trim airspeeds.



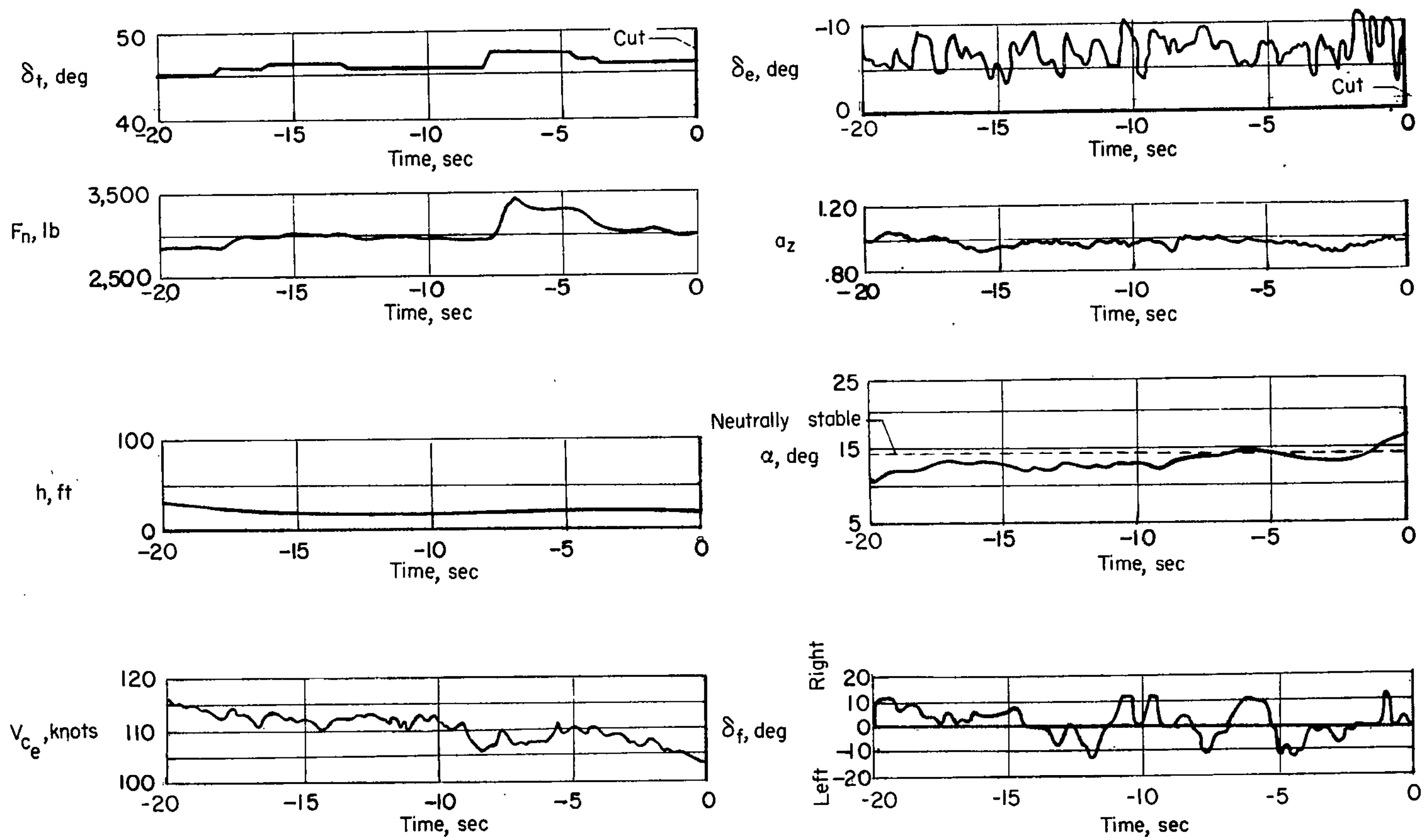
(a) Run 1.

Figure 13.- Time histories of measurements recorded in six field-carrier landings.



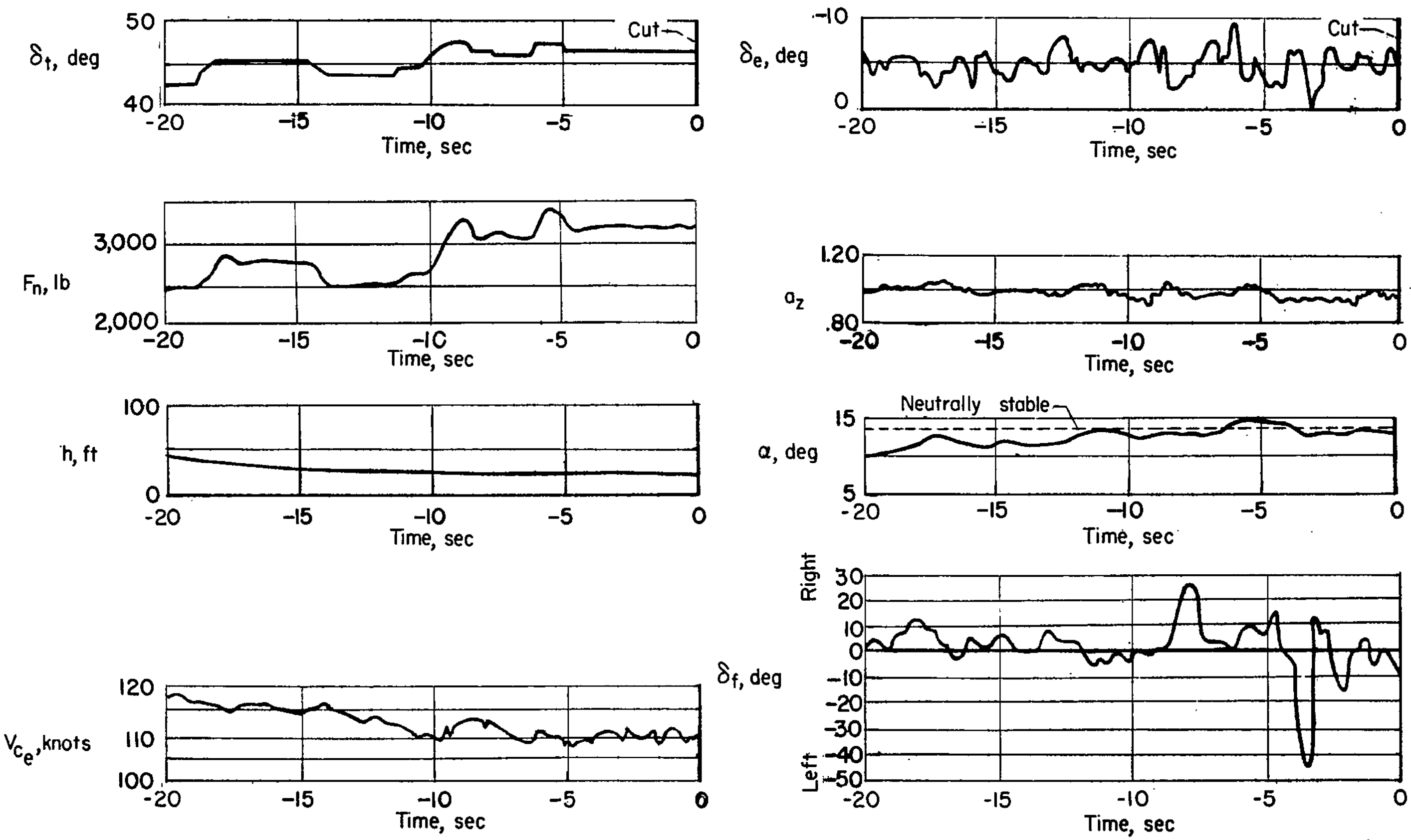
(b) Run 2.

Figure 13.- Continued.



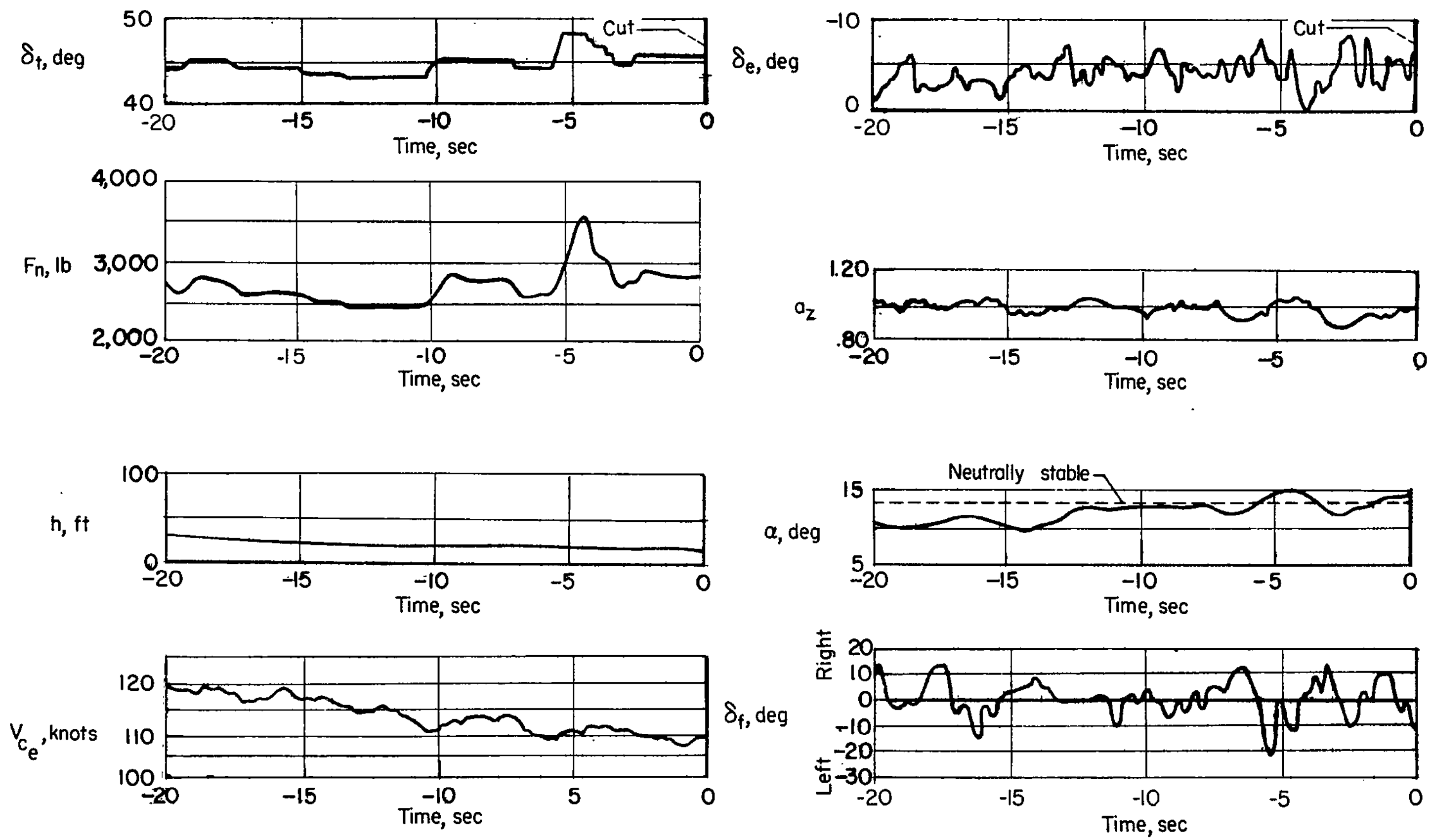
(c) Run 3.

Figure 13.- Continued.



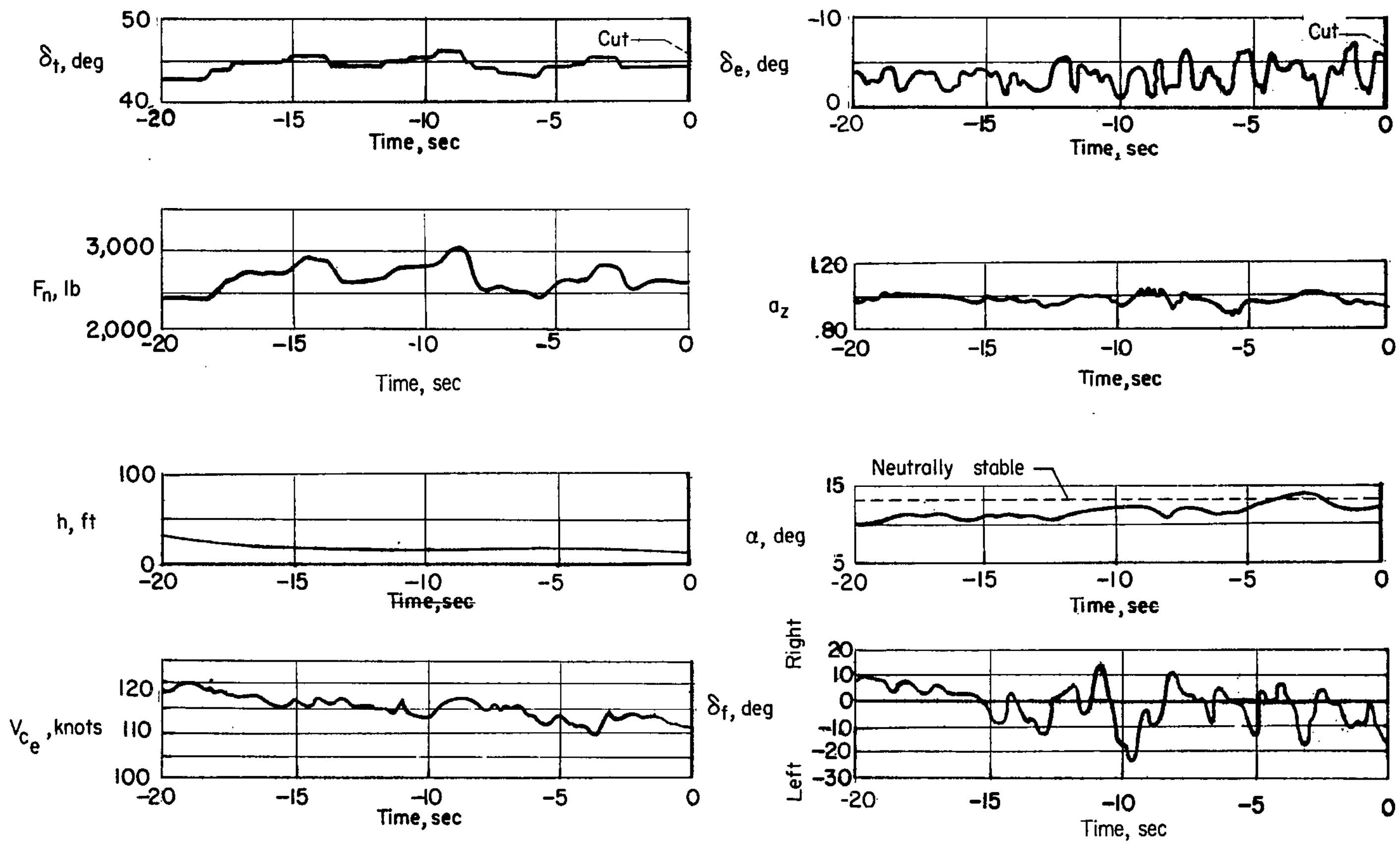
(d) Run 4.

Figure 13.- Continued.



(e) Run 5.

Figure 13.- Continued.



(f) Run 6.

Figure 13.- Concluded.

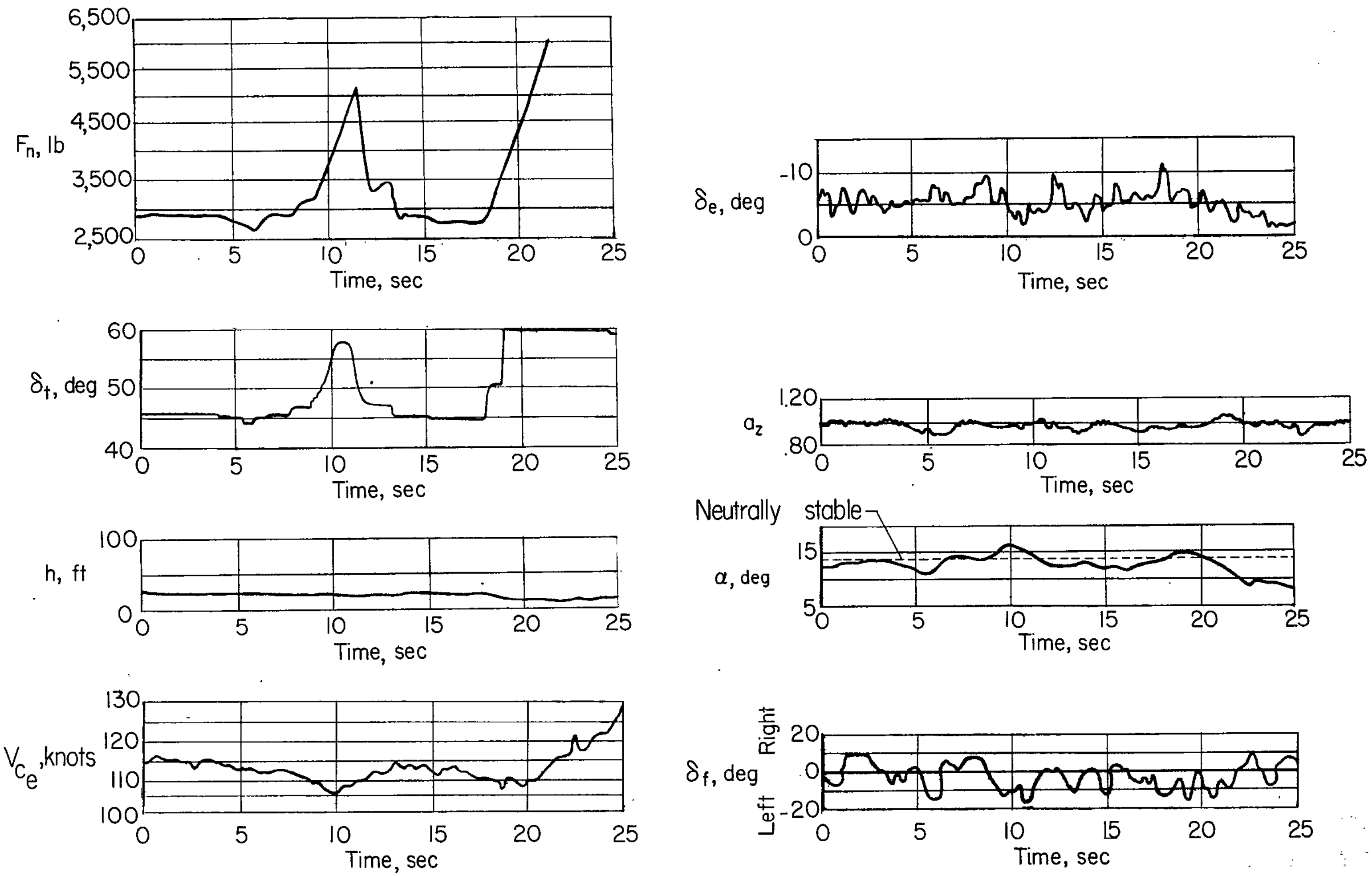


Figure 14.- Time histories of measurements recorded in a wave-off maneuver.

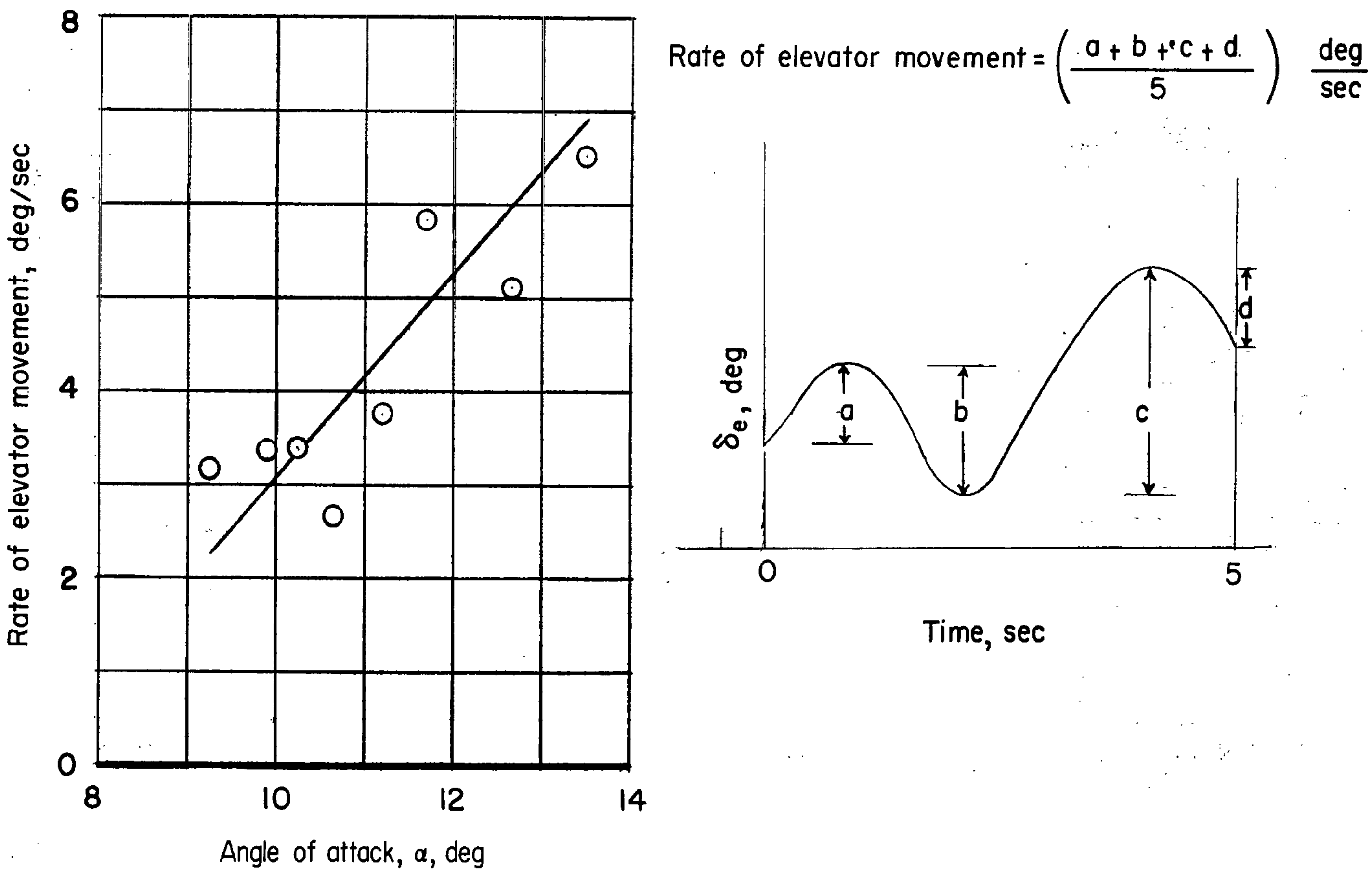


Figure 15.- Average variation of rate of elevator movement with angle of attack during the last 20 seconds prior to throttle cut for field-carrier landings. (Each point based on time interval of 85 seconds.) Illustration of determination of rate of elevator movement also shown.

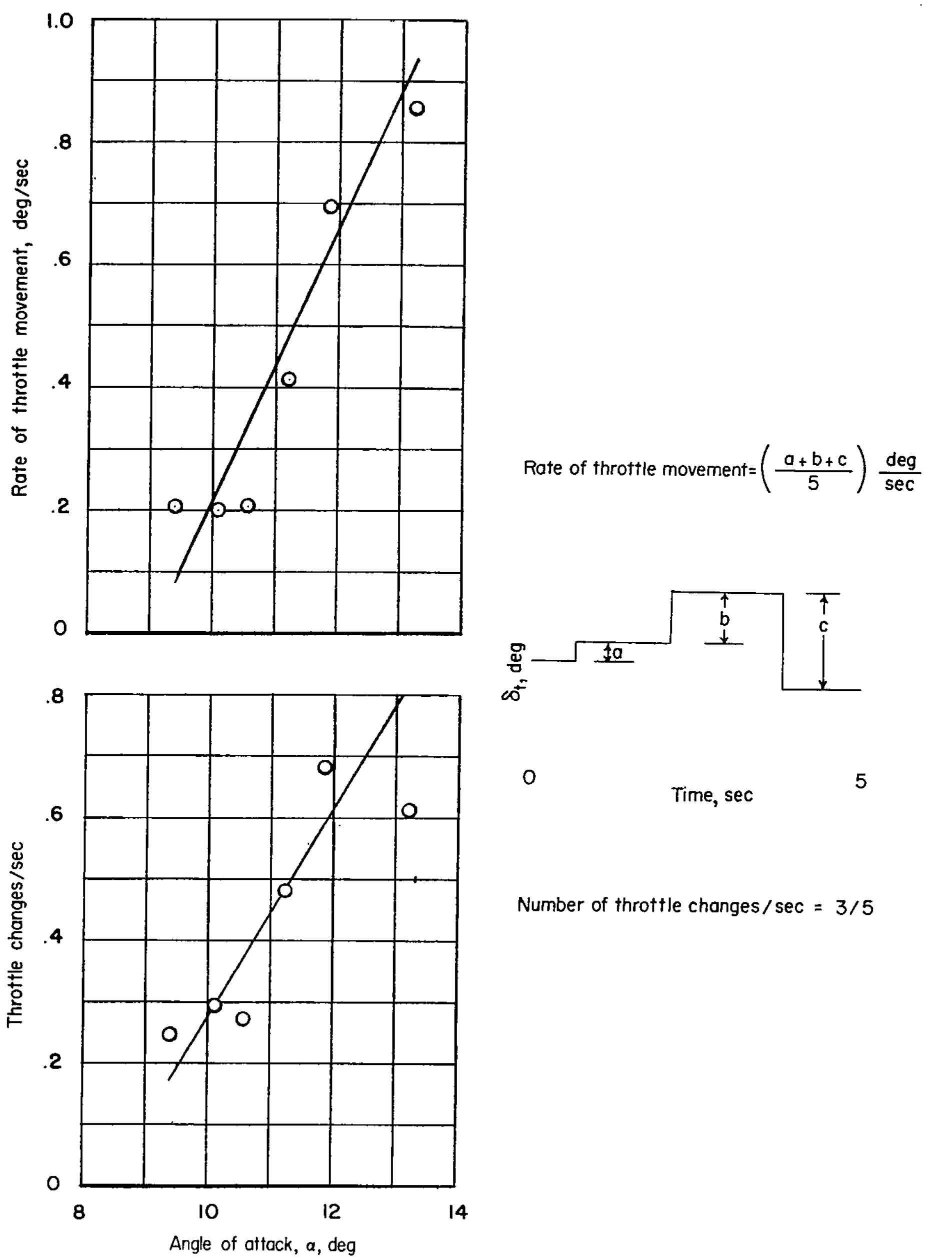


Figure 16.- Variation of rate and number of throttle changes per second with angle of attack during the time interval from 5 to 20 seconds before throttle cut for field-carrier landings. (Each point based on time interval of 85 seconds.) Illustration of determination of rate of throttle movement and number of throttle changes per second also shown.

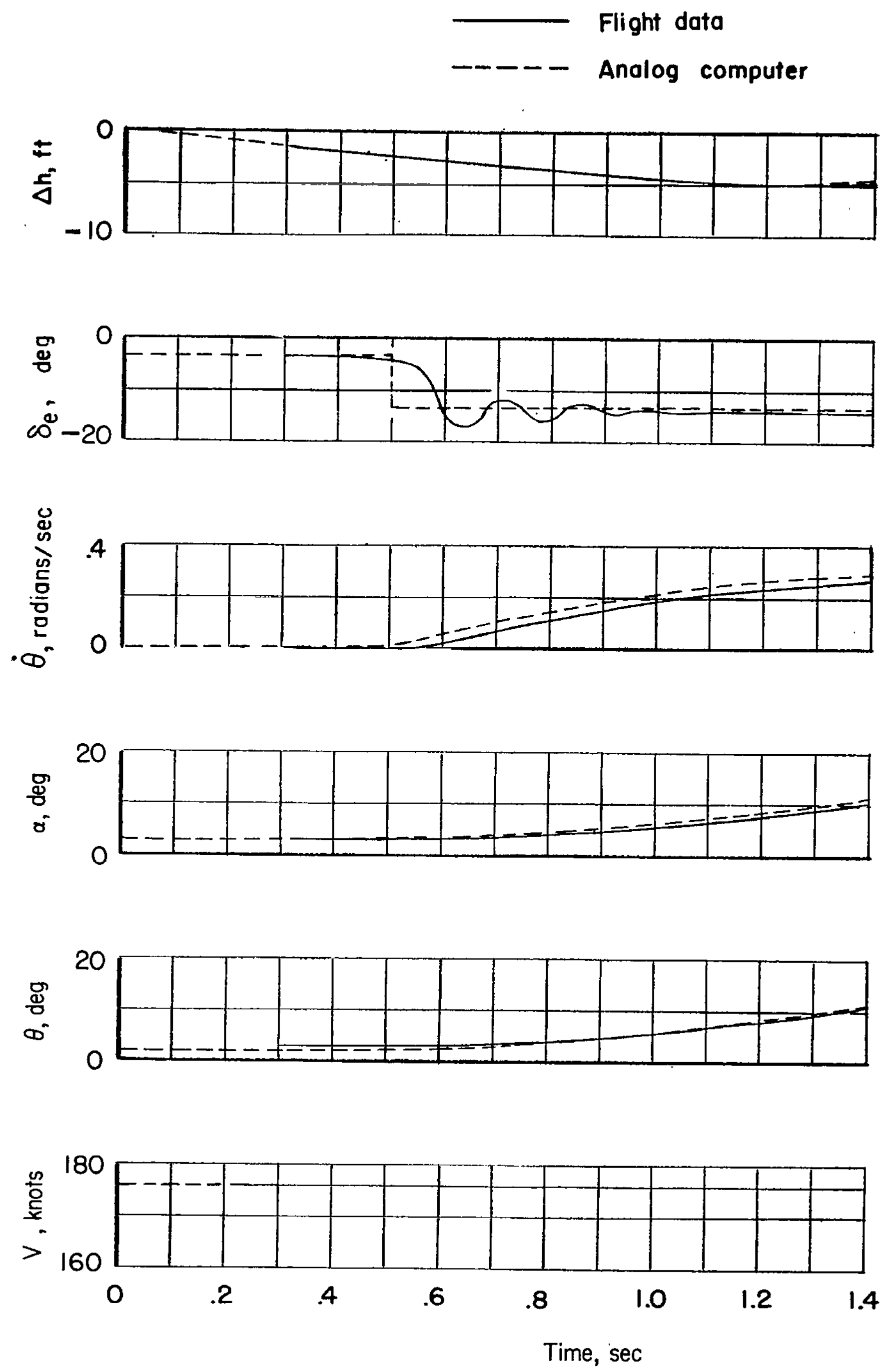
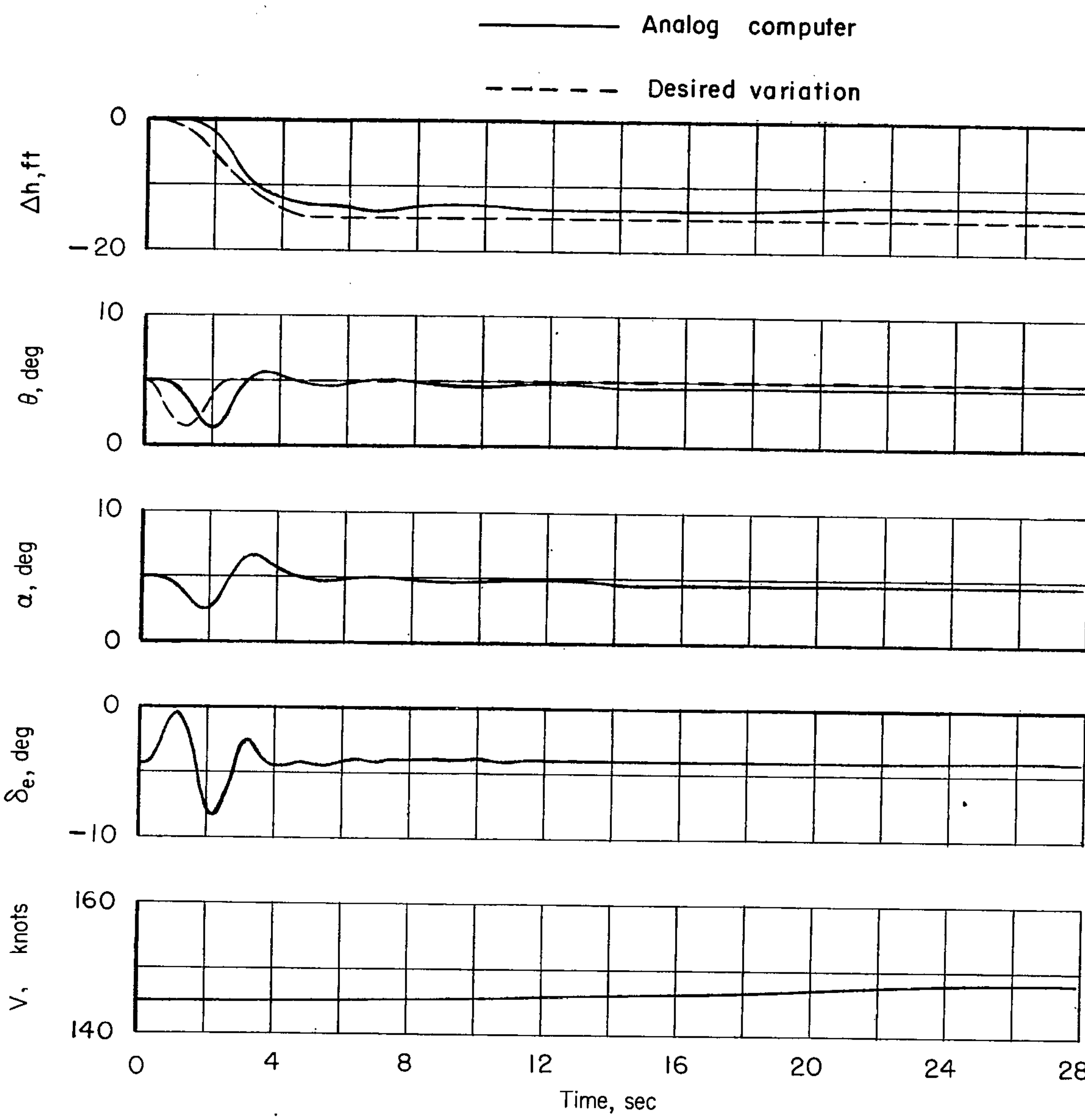
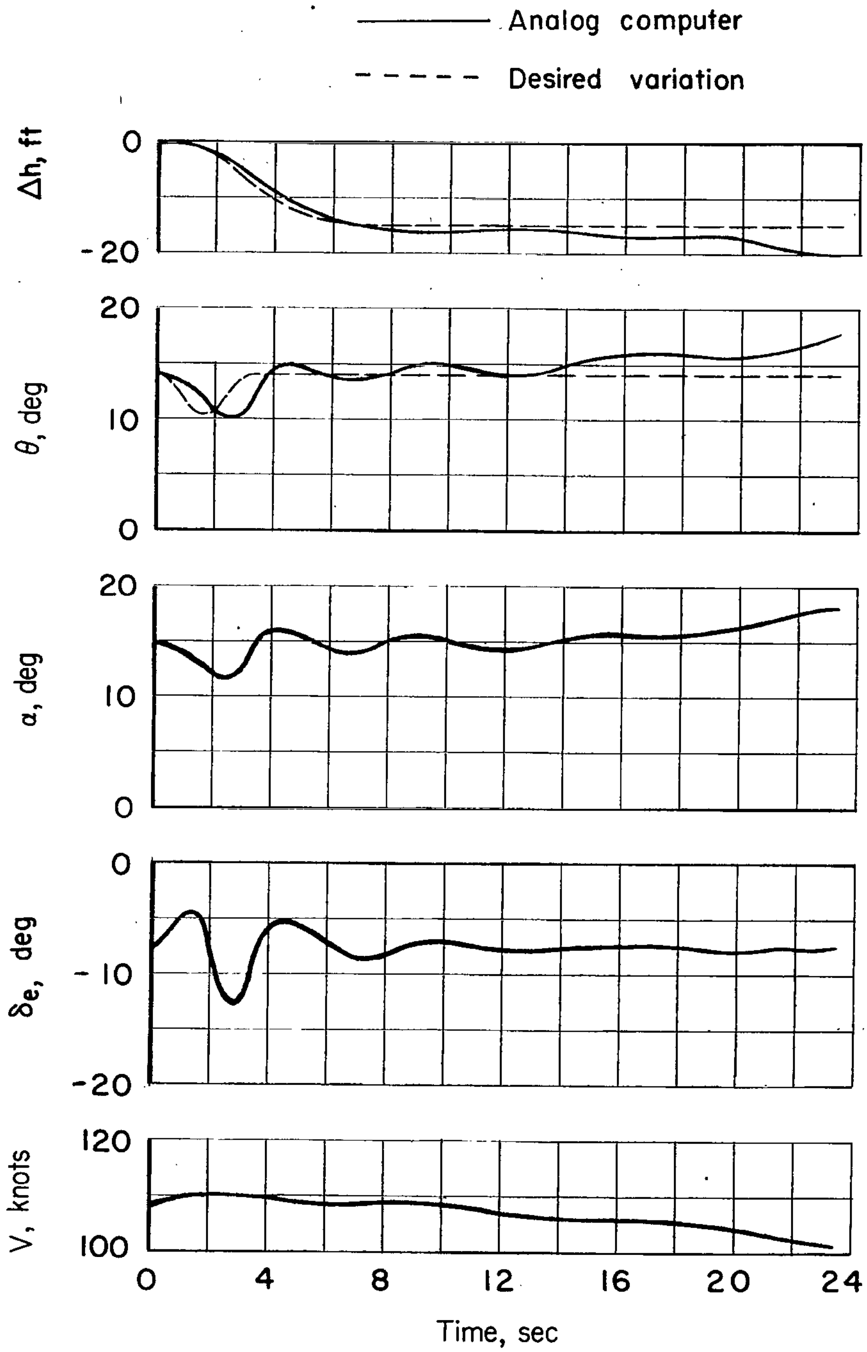


Figure 17.- Comparison of flight data during a pull-up with airplane motions determined by analog computer.



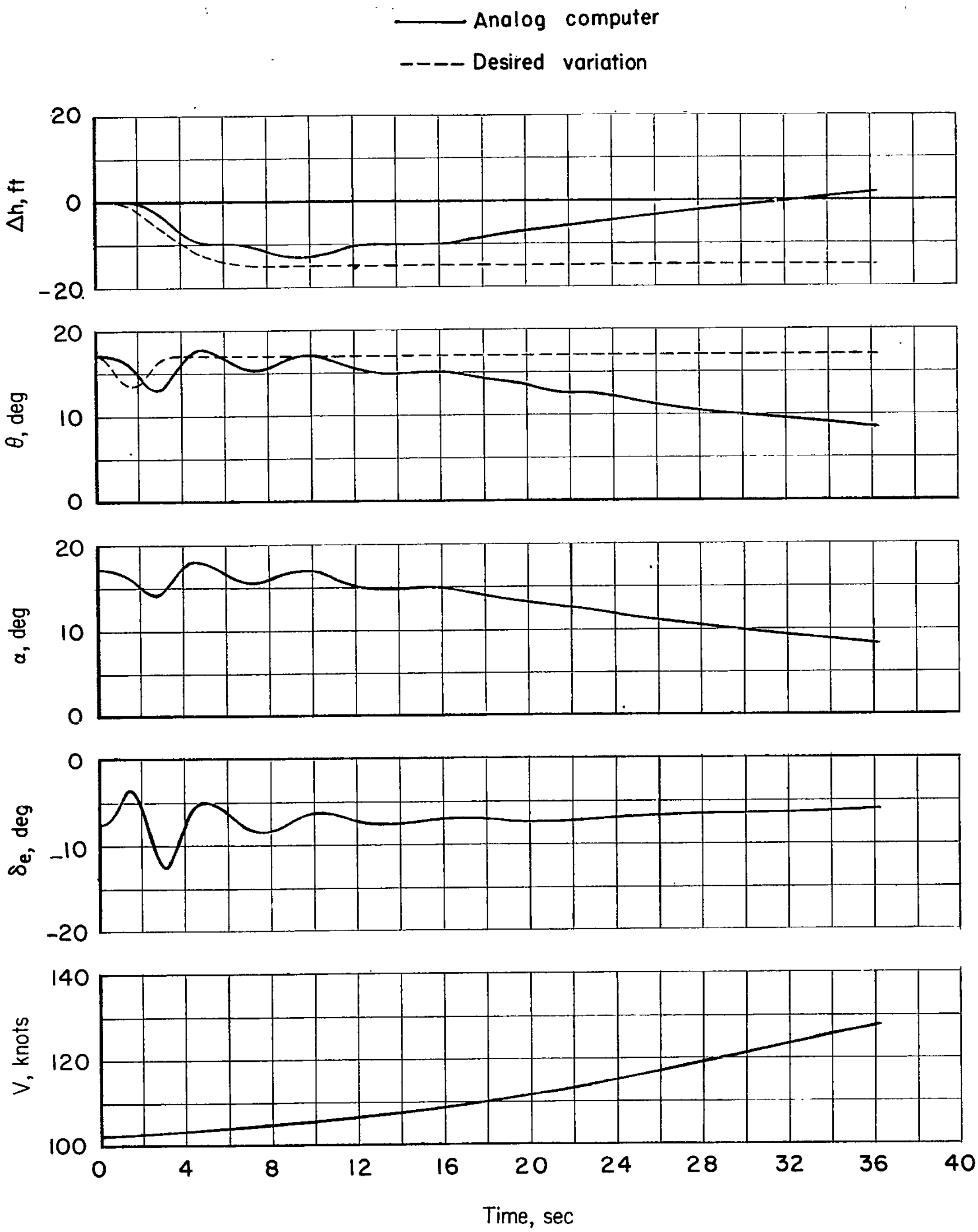
(a) $V_o = 145$ knots.

Figure 18.- Time histories of airplane motions computed by analog simulation compared with desired variations of altitude and attitude angle used as inputs to autopilot.



(b) $V_o = 109$ knots.

Figure 18.- Continued.



(c) V_o = 102 knots.

Figure 18.- Concluded.

NACA - Langley Field, Va.